NOV 1 [illegible]

982-G-15

TD 2.36: 85-11

455

TRAFFIC CONTROL SYSTEMS HANDBOOK

FHWA-IP-85-11

ORIGINAL

U.S. Department
of Transportation

Federal Highway
Administration

REVISED - APRIL 1985

CDO

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The contents of this report reflect the views of the contractor, who is responsible for the accuracy of the date presented herein. The contents do not necessarily reflect the official policy of the Department of Transportation. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

FOREWORD

In 1976, the Federal Highway Administration published the original Traffic Control Systems Handbook as a compendium of traffic control systems technology. The Handbook has been a very effective document in fostering understanding and acceptance of the latest available technology, and it has contributed to accelerated implementation and use of proven traffic control techniques.

Since 1976, significant technological and managerial changes have taken place in many aspects of traffic control systems. These changes, coupled with a more sophisticated community of system users, have created a need to revise the original Handbook. Examples of these changes include: microprocessor-based controllers and system masters, advances in communications, distributed-multi-level intersection control, freeway corridor control and driver information systems, optimization of signal timing plans, and time-based signal coordination. There are also better procedures for selecting system configurations, assessing maintenance and staffing requirements, and planning system procurements. Therefore, the revised Handbook reflects the current state of the art and is focused toward the experienced user. It will serve as a basic guideline to aid practicing traffic engineers in the planning, designing, implementation, and operation of new and effective traffic control systems. The Handbook will also serve as an excellent training aid in the field of traffic control systems.

The revised Handbook is the product of an HP&R pooled funds study participated in by the States of California, Connecticut, Florida, Maryland, Texas, and Washington.

Distribution of the Handbook, including the Executive Summary, is being made to the Regional and Division Offices according to distribution numbers requested by the field offices and the States. Questions concerning the Handbook should be directed to Mr. Charles R. Stockfisch, Office of Implementation (FTS 285-2368). Copies will also be available from the National Technical Information Service, Springfield, VA 22161.

RJ Betsold
R. J. Betsold
Director, Office of Implementation
Federal Highway Administration

BLANK PAGE

ACKNOWLEDGMENTS

The development of this updated version of the *Traffic Control Systems Handbook* has been the result of a pooled funding effort of the states of California, Connecticut, Florida, Maryland, Texas, and Washington. Each state not only provided funding support, but also contributed the technical expertise of knowledgeable professionals to form a Technical Review Committee. The extensive contributions of the following members of the Technical Review Committee are gratefully acknowledged:

California Department of Transportation (Caltrans)
Mr. Harold Garfield
Assistant Traffic Engineer

Connecticut Department of Transportation
Dr. Charles E. Dougan
Director of Research

Florida Department of Transportation
Mr. Gary Price
Deputy State Traffic Operations Engineer

and

Mr. Jack Brown
Deputy State Traffic Operations Engineer

Maryland Department of Transportation
Mr. Scott Parrish
Chief, Bureau of Research

Texas Department of Highways and Public Transportation
Mr. Herman Haenel
Supervising Traffic Engineer

Washington State Department of Transportation
Mr. Wayne Gruen
State Traffic Engineer

and

Mr. John Murray
Former State Traffic Engineer

TRAFFIC
CONTROL
SYSTEMS
HANDBOOK

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS . . . iii

LIST OF FIGURES . . . vii

LIST OF TABLES . . . x

EXECUTIVE SUMMARY . . . ES.1 -XIV

Chapter

1. INTRODUCTION . . . 1.1

Handbook Scope and Objectives . . . 1.3
Role and Impact of Traffic Signal Systems . . . 1.3
Transportation Systems Management (TSM) Relationship . . . 1.4
Background of System Development . . . 1.4
Present Status — Traffic Surveillance and Control Systems . . . 1.6
How to Use This Handbook . . . 1.6
References . . . 1.6

2. AVAILABLE CONTROL SYSTEMS TECHNOLOGY . . . 2.1 -9

Introduction . . . 2.3 -11
Control System Functions . . . 2.3
Range of Agency Needs . . . 2.4 -12
Range of Available Options . . . 2.5 -13
Available Technology . . . 2.7 -15
A Look to the Future . . . 2.10 -18
References . . . 2.11 -19

3. CONTROL CONCEPTS — URBAN STREETS . . . 3.1 -21

Introduction . . . 3.5 -25
Control Variables . . . 3.5
Sampling . . . 3.8 -28
Filtering and Smoothing . . . 3.9 -29
Traffic Signal Timing Parameters . . . 3.9
Traffic Signal Phasing . . . 3.9
Isolated Intersections . . . 3.11 -31
Arterial Street Control . . . 3.22 -42
Closed Network Control . . . 3.28 -48

Chapter Page

Areawide System Control . . . 3.42-62
Incremental Benefits of Different Levels of Control . . . 3.45-65
Special Controls . . . 3.51-71
Measures of Effectiveness . . . 3.62-82
References . . . 3.67-87

4. CONTROL CONCEPTS — FREEWAYS . . . 4.1-93

Introduction . . . 4.3-95
Entrance Ramp Control . . . 4.7-99
Exit Ramp Control . . . 4.33-125
Mainline Control . . . 4.33
Corridor Control and Surveillance . . . 4.39-131
Available Computer Software . . . 4.50-142
High-Occupancy Vehicle Priority Control . . . 4.56-148
References . . . 4.64-156

5. DETECTORS . . . 5.1-163

Introduction . . . 5.3-165
Types of Detectors . . . 5.3
Detector Operations Summary . . . 5.9-171
Vehicle Detector Location and Configuration . . . 5.15-177
Future Detector Technology . . . 5.31-193
References . . . 5.33-195

6. LOCAL CONTROLLERS . . . 6.1 -197

Introduction . . . 6.3 -199
Types of Operation . . . 6.3
Range of Applications . . . 6.5 -201
Hardware Evolution . . . 6.7 -203
Types of Local Controllers . . . 6.8 -204
Pretimed Controllers . . . 6.8
Full-Actuated Controllers . . . 6.10 -206
Model 170 and NEMA Controllers . . . 6.21 -217
Local Controller Coordination . . . 6.28 -224
Factors in Controller Selection . . . 6.30 -226
References . . . 6.32 -228

7. SYSTEM MASTERS . . . 7.1 -229

Chapter *Page*

Introduction 7.3-231
Arterial and Small Network Systems 7.4-232
Time-Base Coordination 7.14-242
Distributed, Closed-Loop Systems 7.15-243
Basic Computerized Signal System 7.25-253
UTCS Software 7.25
Network Control System Masters 7.31-259
Optional Control and Other Software Features 7.34-262
Control Center Features 7.37-265
References 7.41-269

8. COMMUNICATIONS 8.1-270

Introduction 8.3-272
Basic Concepts 8.4-273
Alternative Communications Links 8.15-284
Communication System Planning and Evaluation 8.25-294
Additional Information Sources 8.31-300
References 8.33-302

9. DRIVER INFORMATION SYSTEMS 9.1-304

Introduction 9.3-306
Static Signs 9.3
Diagrammatic Signs 9.4-307
Changeable Message Signs (CMS) 9.4
Transportable Signs 9.11 314
Highway Advisory Radio (HAR) 9.13-316
Motorist Aid Systems 9.18-321
Citizen Band (CB) Radio 9.20-323
Commercial Radios 9.22 325
Cellular Mobile Phone System 9.22
Design Guide 9.23-326
Transportation Management Center 9.23
Lane-Use Control Signals 9.25
References 9.25-328

10. SELECTION OF A SYSTEM 10.1 330

Chapter *Page*

Introduction 10.3-331
Federal-Aid Requirements 10.3
System Selection Process 10.5-333
References . . . . 10.10 -338

11. DESIGN AND IMPLEMENTATION . . . . 11.1 -339

Introduction . . . . 11.3 -341
System Implementation 11.3
Procurement Approach . . . . 11.4 -342
Design Plans and Specifications . . . . 11.6 -344
Deliverable Services . . . . 11.11 -349
Project Management . . . . 11.14 -352
Implementation Pitfalls . . . . 11.17 -355
References . . . . 11.22 -360

12. SYSTEM MANAGEMENT . . . . 12.1 -361

Introduction . . . . 12.3 -363
A System Management Team Concept 12.3
Operation of Traffic Control Systems . . . . 12.4 -364
Staff Requirements and Organization . . . . 12.11 -371
Maintenance of Traffic Control Systems . . . . 12.13 -373
Evaluation of Traffic Control Systems . . . . 12.18 -378
References . . . . 12.22 -382

APPENDIX A: Excerpt from Federal-Aid Highway Program Manual . . . . A.1 -383

ACRONYMS . . . . AC.1 -389

GLOSSARY . . . . G.1 -391

INDEX . . . . I.1 -420

LIST OF FIGURES

Figure *Page*

2.1. Basic functions of a traffic control system 2.3
3.1. Speed measurements using presence detectors 3.6
3.2. Headway determination 3.8
3.3. Filtering equation 3.9
3.4. Single-ring 2-phase signal sequence 3.9
3.5. Single-ring 4-phase signal sequence 3.10
3.6. Dual-ring left-turn phasing options 3.11
3.7. Primary phasing options for 8-phase dual-ring control (left turns first) 3.12
3.8. Traffic detection on intersection approach 3.13
3.9. Schematic of actuated phase interval 3.13
3.10. Queue discharge across the stop line 3.15
3.11. Example intersection 3.17
3.12. Cycle length relationship to capacity and delay 3.20
3.13. Signal networks 3.22
3.14. Time-space diagram and graphic technique 3.23
3.15. Typical signal network 3.29
3.16. Closed network signal timing 3.30
3.17. Preferential flow 3.30
3.18. Principles of the SCOOT traffic model 3.36
3.19. Section control configuration 3.39
3.20. Types of signal systems 3.43
3.21. Centralized signal control system 3.44
3.22. Decentralized signal control system 3.46
3.23. Schemes of multijurisdictional control 3.48
3.24. Fuel consumption and emissions of carbon monoxide, hydrocarbons, and nitrogen oxides from driving 1,000 miles at various uniform speeds (for light-duty vehicles) 3.49
3.25. Additional fuel consumption of vehicular speed changes above consumption of continuing at uniform speed (for light-duty vehicles) 3.50

Figure *Page*

3.26. Types of diamond interchanges 3.54
3.27. Three-phase pretimed diamond interchange phasing 3.55
3.28. Four-phase pretimed diamond interchange phasing 3.55
3.29. Four-phase full-actuated diamond interchange phasing 3.57
3.30. Special application frontage road progression 3.57
3.31. Texas diamond interchange controller phasing configuration 3.59
3.32. Three-phase full-actuated diamond interchange phasing 3.59
3.33. Florida urban interchange design and signal phasing 3.60
3.34. Closed circuit television (CCTV) camera and monitors in urban street surveillance and control center in Columbus (Ohio) 3.63
3.35. Time-space diagram for stop and delay computations for urban street control 3.65
3.36. Relationship of percentage of vehicles stopping and approach delay 3.66

4.1. Congestion and the fundamental relationship between flow rate and density 4.4
4.2. Generalized traffic flow relationships 4.5
4.3. Relationship among demand, capacity, and congestion 4.7
4.4. Flow-density relationship and revised relationship among demand, capacity, and congestion 4.7
4.5. Entrance ramp closure by means of automated barriers 4.11
4.6. Example of pretimed entrance ramp metering rate calculation 4.12
4.7. Layout of pretimed entrance ramp metering system 4.13
4.8. Ramp metering signals and advance ramp metering systems 4.14
4.9. General traffic flow model 4.16

Figure *Page*

4.10. Fundamental flow rate-speed-density relationships 4.17
4.11. Typical volume-occupancy plot used in the calculation of entrance ramp metering rates, Chicago (Illinois) 4.20
4.12. Layout of traffic-responsive, entrance ramp metering system 4.22
4.13. Layout of a gap-acceptance merge-control system 4.24
4.14. Integrated entrance ramp control: Example No. 1 — Calculation of pretimed metering rates 4.26
4.15. Integrated entrance ramp control: Example No. 2 — Calculation of pretimed metering rates 4.28
4.16. Integrated entrance ramp control: Example No. 4 — Calculation of pretimed metering rates 4.30
4.17. Schematic representation of integrated entrance ramp control system 4.32
4.18. Relationship between the controllability index and incremental travel-time savings 4.34
4.19. Variable-speed and lane controls tested in Detroit (Michigan) 4.36
4.20. Mainline lane-closure control at freeway-to-freeway interchange in Houston (Texas) 4.37
4.21. Lane-control signal used for mainline lane closure control at freeway-to-freeway interchange in Houston (Texas) 4.38
4.22. Mainlane lane closure used in traffic diversion system in Germany 4.39
4.23. Connector metering installation in San Diego (California) 4.40
4.24. Graphical summary of the theoretical impact of a freeway incident on traffic flow 4.43
4.25. Emergency call box 4.46
4.26. Emergency telephone 4.46
4.27. The BEAR System, Michigan 4.47
4.28. Surveillance control response to a capacity-reducing incident 4.48
4.29. Basic elements of a CCTV system 4.50
4.30. San Bernadino (California) busway 4.57
4.31. Shirley Highway (I-95) HOV express lanes in Washington, D.C. (middle lanes are reserved exclusively for buses and carpools) 4.59
4.32. Authorized vehicle decal 4.61

Figure *Page*

4.33. Typical ramp metering layout with bypass, I-35 W corridor project — Minneapolis (Minnesota) 4.62
4.34. Carpool bypass lane at a metered entrance ramp near Los Angeles (California) 4.63
4.35. Overhead electronic changeable message sign on I-5, Seattle (Washington) 4.63

5.1. Principal components of an inductive loop detector system 5.4
5.2. Nondirectional uncompensated magnetic detector 5.7
5.3. Magnetometer detectors 5.8
5.4. Loop length for low-speed approaches 5.13
5.5. Two methods of multiple-point detection systems for approach speeds up to 55 mph 5.17
5.6. Contrast between small-area and large-area detection 5.18
5.7. Typical detector designs 5.19
5.8. Loop location for extended call-delay call (EC-DC) design with 55-mph approach design speed 5.20
5.9. Detection in left-turn lanes 5.21
5.10. Extended detection in left-turn lanes 5.21
5.11. Powerhead configurations 5.22
5.12. Quadrupole-loop configuration (1-2-1) design 5.22
5.13. Volume profile for links that are candidates for detectorization 5.24
5.14. Possible location of detectors at freeway entrance ramp 5.28
5.15. Typical diamond-loop layout for speed trap 5.29
5.16. Control system options with Wide Area Detection System (WADS) 5.32

6.1. Typical dial unit 6.9
6.2. Typical camshaft 6.10
6.3. Phase sequence for single-ring controller 6.12
6.4. Phase sequence for dual-ring controller 6.13
6.5. Dual-ring basic phase sequence options 6.14
6.6. Example of special phase sequence for conditional service of left-turn phase 6.18
6.7. Special diamond interchange phasing 6.19

Figure *Page*

6.8. Typical detector configuration for 3-phase, lag-lag and 4-phase (with overlap) special sequences . . . 6.21
6.9. Computer-controlled diamond interchange operation . . . 6.22
6.10. Model 170 typical front panel display . . . 6.23
6.11. Two basic phase operations for the Isolated Traffic-Actuated Program . . . 6.25
6.12. Phase sequence option in DIP software . . . 6.27
6.13. Controller selection process . . . 6.30
7.1. Block diagram of flexible advanced computer traffic signal (FACTS) system . . . 7.7
7.2. Operational layout for dynamic responsive traffic signal (DARTS) system . . . 7.9
7.3. Examples of application of Basic Arterial System (BASYS) software programs . . . 7.11
7.4. Block diagram of Eureka Distributive Intelligence Progression System (EDIPS) . . . 7.16
7.5. JHK distributed traffic control and surveillance system block diagram . . . 7.19
7.6. Block diagram of TRANSYT 3800 closed-loop system . . . 7.21
7.7. Block diagram of KMC-10,000 incremental master system . . . 7.22
7.8. Safetran CM 1655 system block diagram . . . 7.24
7.9. Block diagram of Basic control system . . . 7.26
7.10. Urban traffic control system (UTCS) extended software priority levels . . . 7.29
7.11. Block diagram of a typical traffic control system . . . 7.31
8.1. Examples of direct-wire switching techniques . . . 8.5
8.2. Point-to-point interconnection . . . 8.6
8.3. Multidrop interconnection . . . 8.7
8.4. Application of multidrop scheme in a large signal network . . . 8.7
8.5. An amplitude-modulated signal . . . 8.8
8.6. A 2-frequency, frequency-shift-keyed signal . . . 8.9
8.7. A phase-shift-keyed signal . . . 8.9
8.8. The communications channel and its capacity . . . 8.9

Figure *Page*

8.9. Channels and guardbands utilized in frequency division multiplexing (FDM) with frequency-shift keying . . . 8.11
8.10. Asynchronous transmission . . . 8.12
8.11. Typical time division multiplexing (TDM) message format . . . 8.13
8.12. Properties of twisted wire pairs and their effects on interference and crosstalk . . . 8.16
8.13. Central control interface equipment for coaxial cable system . . . 8.19
8.14. Intersection control interface equipment for coaxial cable system . . . 8.20
8.15. Typical cable television (CATV) layout . . . 8.21
8.16. Cable television (CATV) channel splits . . . 8.22
8.17. Fiber-optic repeater transceiver . . . 8.23
8.18. Block diagram of laser transceiver unit . . . 8.24
8.19. Laser communications system . . . 8.25
8.20. Central-type architecture block diagram . . . 8.28
8.21. Hierarchical-type distributed processing architecture . . . 8.29
8.22. Network-type distributed processing architecture . . . 8.30
9.1. Static sign . . . 9.5
9.2. Diagrammatic sign for exit only on left-hand interchange land drop . . . 9.6
9.3. Foldout sign . . . 9.9
9.4. Examples of rotating drum signs Duluth (Minnesota), top; Dutch-John (Utah), bottom . . . 9.10
9.5. Lamp matrix sign . . . 9.11
9.6. Closeup of 2-position disc matrix sign module . . . 9.12
9.7. Disc matrix sign, I-70 West, Denver (Colorado) . . . 9.12
9.8. Tri-Color sign element . . . 9.13
9.9. Examples of transportable CMS's used for major incident response . . . 9.15
9.10. Typical highway advisory radio (HAR) antennas . . . 9.16
9.11. Automatic highway advisory radio (AHAR) . . . 9.19
9.12. CB/Aids basic concept . . . 9.23
9.13. CB digital adapter . . . 9.23
9.14. Relationship of the components of a driver information system . . . 9.24
9.15. Lane-use control signals . . . 9.25
10.1. Example of utility calculations . . . 10.7

Figure *Page*

10.2. Utility-cost comparison of alternative systems 10.10

11.1. Systems management matrix 11.4

11.2. Sample specification — system acceptance test 11.15

11.3. Initial implementation PERT chart, Chicago (Illinois) central business district (CBD) traffic control system 11.17

11.4. Example of CPM network diagram 11.19

Figure *Page*

11.5. Greensboro (North Carolina) traffic control project milestone schedule 11.20

12.1. System management team concept 12.4

12.2. Typical daily control center log form 12.6

12.3. Typical system control and operations architects 12.7

12.4. Typical aggregate MOE contour timing plan graphic 12.8

12.5. Typical flow chart for system modification and update 12.9

LIST OF TABLES

Table *Page*

2.1. Control systems functions and features 2.8

3.1. Vehicle headway data 3.15

3.2. Capacity values 3.20

3.3. Comparison of UTCS control techniques 3.33

3.4. Results of SCOOT in Central Glasgow 3.37

3.5. Results of SCOOT in Coventry 3.37

3.6. Summary of Toronto experiments 3.38

3.7. Rates of fuel consumption and emissions and total vehicle operating costs for an idling engine 3.50

3.8. Composite emission factors (grams/veh-mi) for low and high altitudes 3.51

3.9. Composite emission factors (grams/veh-mi) for the State of California 3.52

3.10. Automobile running cost at uniform speed on selected grades (dollars per 1,000 veh-mi) 3.52

3.11. Excess automobile running cost of speed change cycles above cost of continuing at initial speed (dollars per 1,000 speed change cycles) 3.53

Table *Page*

3.12. Excess hours consumed for speed change cycle above continuing at initial for speed for automobiles (hours per 1,000 speed change cycles) 3.55

3.13. Travel time reduction and fuel consumption impacts of a hypothetical traffic signal system improvement for an area of one million population 3.56

3.14. Example estimates of daily area-wide impacts of a comprehensive traffic control system improvement program (composed of traffic signal system interconnection, timing plan optimizations, and master control system improvements) 3.57

3.15. Summary of annual costs of various traffic signal system improvements 3.58

3.16. Cost-effectiveness analysis of hypothetical traffic signal system improvement program for an urban area of one million 3.58

4.1. Types of congestion by percentage for Los Angeles (California) 4.4

Table *Page*

4.2. Capacity reduction resulting from shoulder and lane blockages, Gulf Freeway (Houston, Texas) 4.7
4.3. Summary of reported benefits of entrance ramp metering systems 4.15
4.4. Summary of various traffic-responsive, entrance ramp metering strategies 4.19
4.5. Summary of various traffic-responsive, entrance ramp metering configurations for system operation 4.20
4.6. Summary of reported benefits of traffic-responsive freeway ramp metering systems 4.21
4.7. Characteristics of exclusive HOV roadways on grade-separated facilities 4.58
4.8. Characteristics of contraflow HOV lanes on grade-separated facilities 4.59
4.9. Characteristics of concurrent flow HOV lanes on grade-separated facilities 4.60

5.1. Calculated loop inductance in microhenries 5.5
5.2. Types of detectors 5.10
5.3. Summary of detection locations and related timing for basic actuated controller units (locking detection memory) 5.12
5.4. Dilemma zone boundaries 5.13
5.5. Conventional detector-controller unit configurations for high-speed approaches 5.14
5.6. Summary of cost-effectiveness freeway sensor placements for detecting incidents 5.31

6.1. Range of applications to street intersection control 6.6
6.2. Current status of selected Model 170 software programs 6.24
6.3. Items for comparison of NEMA and Model 170 controller units 6.28

7.1. Principal features of custom-designed systems 7.33
7.2. Principal features of package-type systems 7.34
7.3. Summary of available public domain software 7.39

8.1. User-owned versus leased wire-pair cable 8.17
8.2. System weights 8.32
8.3. Compliance factors for candidate systems 8.32
8.4. Candidate system utilities 8.33

9.1. Sign types and uses 9.4
9.2. Applications of changeable message and other types of real-time displays 9.6
9.3. Sign control and operation techniques 9.8
9.4. Types of changeable-message sign displays 9.9
9.5. Characteristics of various citizen-band (CB) radio motorist aid applications 9.21

10.1. Utility measure weights 10.8
10.2. Example freeway goals and subgoals 10.9

11.1. Initial PERT analysis, Chicago (Illinois) CBD traffic control system 11.18

12.1. Examples of staffing for management of computer-controlled systems 12.12
12.2. Summary of 1982 expenses for timing a 46-intersection network 12.15
12.3. Criteria for developing measures of effectiveness (MOE's) 12.21

Technical Report Documentation Page

1. Report No.
FHWA-IP-85-12

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Traffic Control Systems Handbook — Executive Summary
Revised Edition - 1985

5. Report Date
April 1985

6. Performing Organization Code

7. Author(s)
R. Wilshire, R. Black, R. Grochoske, J. Higinbotham

8. Performing Organization Report No.

9. Performing Organization Name and Address
PAWA-Winkelmann and Associates, Inc.
12660 Coit Road
Dallas, TX 75251

10. Work Unit No. (TRAIS)
32ZQ 918

11. Contract or Grant No.
DOT-FH-61-83-C-00007

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
Office of Implementation
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report
February 1983 - April 1985

14. Sponsoring Agency Code

15. Supplementary Notes
FHWA Contract Manager: Charles R. Stockfisch, HRT-20

16. Abstract

Within the broad spectrum of transportation systems management (TSM), traffic control systems play a key role in the efficient operation of urban streets and freeways. In the mid-1970s, FHWA published the original *Traffic Control Systems Handbook* as a compendium of available technology and practice. In the intervening years, control systems technology and hardware advances, permitted by the application of the microprocessor, have contributed to widespread use of such systems.

This revision retains much of the valuable material and basic scope of the original Handbook, but updates discussions of concepts and hardware to reflect current state of the art. Further, it is focused toward the more experienced signal and control systems designer and user, with discussions of actual experience and pitfalls. Topics addressed in the Handbook include:

- Available systems technology
- Control concepts — urban streets
- Control concepts — freeways
- Detectors
- Local controllers
- System masters
- Communications
- Driver information systems
- Selection of a system
- Design and implementation
- System management

17. Key Words
Communications
Controller assemblies
Control system masters
Control systems
Detectors
Freeway management
Freeway operations
Incident detection
Ramp metering
Surveillance and control

18. Distribution Statement
This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
3

22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

EXECUTIVE SUMMARY

INTRODUCTION

Urban mobility depends to a great extent on the effective utilization of urban streets and freeways. While the actual provision of capacity for mobility through the construction of transportation facilities is accepted as a prerequisite, it must be recognized that efficient operation is a necessary partner of transportation facility design. Traffic control systems, then, *do not create capacity*. They simply *provide a significant tool* to facilitate the full utilization of available capacity.

Significant advances have been made in traffic control systems technology during the past decade. Many of the advances are the direct result of the microprocessor and associated revolutionary advances in electronics technology. Today, agencies with responsibility for traffic control systems are offered a wide range of choices with respect to hardware and operational features, many of which are implemented through software. The resulting real-time control systems implement control functions of data collection, decision-making, execution, verification, and evaluation in a closed-loop fashion with a high level of sophistication and control flexibility.

HANDBOOK SCOPE AND OBJECTIVES

In the mid-1970s, the Federal Highway Administration (FHWA) developed and published a *Traffic Control Systems Handbook* to present basic technology used in planning, designing, and implementing traffic surveillance and control systems for urban street and freeway applications. Because of its timeliness, the Handbook was useful in fostering understanding and acceptance of such systems and contributed to accelerated implementation and use of proven advances in traffic surveillance and control.

In the intervening years, hardware advances made possible by the microprocessor and by the growth of an experienced community of system users have created a need to update the original Handbook. This updated version has been developed with two overall purposes in view:

- To retain valuable material and basic scope of the original Handbook, but update discussion of concepts and equipment to reflect the current state of the art
- To focus the Handbook toward a more experienced user

Even with these shifts, the major specific objectives of this updated version of the *Traffic Control Systems Handbook* remain as follows:

- Provide a compendium of existing traffic control systems technology
- Facilitate the understanding of the basic elements of traffic control systems
- Aid the understanding and application of new technology
- Broaden the viewpoint of the field of traffic control
- Serve as a basic guideline to aid the practicing traffic engineer in planning, designing, implementing, and operating new and effective traffic control systems
- Serve as a training aid in the field of traffic control systems

ROLE AND IMPACT OF TRAFFIC SIGNAL SYSTEMS

No other device has such a daily impact on virtually every citizen as does the common, ever-present traffic signal. The trip to work is punctuated by stops at traffic signals, even on uncongested routes. School children obediently wait for the traffic signal to interrupt traffic so they can cross a busy thoroughfare. Drivers place their physical safety and that of their passengers confidently in the signal's ability to give them the right-of-way.

A signal's necessity is accepted by the citizen, and in fact demanded in some cases, to assure safety and mobility. The same citizen quietly assumes that the operating agency knows how to best operate the signals, and reluctantly reports only the most obvious failures. Inefficient operation annoys some but produces no ground swell of public reaction, even though such operation is silently stealing dollars from the user's pocket in increased fuel costs, longer trip times, etc. In the user's view, the signals are working. If they are suboptimal, it becomes a concern but not a crisis.

Research and actual application have demonstrated the effectiveness of signal system improvements in reducing

VII

delays, stops, fuel consumption, vehicle emission of pollutants, etc. A recent overview analysis of the impacts of traffic control system improvements prepared for the FHWA Office of Planning makes the following statement:

> The systematic *optimization of signal timing plans* in any type of signal system, regardless of the degree of advancement inherent in the master control system, is an essential continuing element of traffic control system management. Evaluation data from a variety of types of signal systems indicate that optimization of signal timing plans, carried out without necessitating any hardware modifications, results in an average *project level* improvement in speed or travel time of *12 percent* (*1*).

The report further indicates that each dollar spent in signal timing optimization yields 35 to 48 reduced hours of vehicle operation — making it the most cost-effective measure observed. Having signal equipment that makes such frequent timing changes possible and reasonably easy then becomes very important.

HANDBOOK CONTENT

Chapters

The *Traffic Control Systems Handbook* is a single-volume, loose-leaf publication containing twelve chapters, with a glossary and a list of acronyms. It retains the basic systems engineering organizational format used earlier. The general content of the Handbook can be visualized by examining the chapter titles which are listed as follows:

1. Introduction
2. Available Control Systems Technology
3. Control Concepts — Urban Streets
4. Control Concepts — Freeways
5. Detectors
6. Local Controllers
7. System Masters
8. Communications
9. Driver Information Systems
10. Selection of a System
11. Design and Implementation
12. System Management

The following portions of the Executive Summary will briefly review the context and organization of the material in the Handbook in the sequential manner of its presentation.

Range of Available Options

Chapter 2 of the Handbook presents a general overview of the traffic control systems field. It is intended for the casual reader who needs only summary information, and it serves as a directory for all users to the location of detailed discussions. Overview information is presented concerning equipment and control concepts, along with discussions of jurisdictional factors to consider in the search for an appropriate control system. Described are control system functions, the widespread range of agency needs, and available options for system hardware and control features. The importance of a commitment to maintenance and staffing to achieving successful operation is emphasized. A brief look toward probable future developments is also presented.

Control Concepts

A basic understanding of concepts and strategies of operation that can be applied to control the movement of traffic is a necessary first step. For convenience, these concepts are presented separately for freeways and urban streets.

Urban Street Control Concepts. Traffic control concepts for urban streets are considered in three basic categories:

- Individual or isolated intersection control
- Arterial intersections or open network control
- Closed network control

These three basic types of signal control have in the past been viewed as separate systems, perhaps requiring unique hardware. Advancing technology permits the consideration of controlling all signals with similar hardware, yet providing control tailored to the specific requirements of each intersection. In this way, true areawide control systems are considered.

The Handbook examines two basic approaches to areawide system control. The first, a centralized approach, is characterized by having all the decision-making and surveillance capability at one geographic location and on one level. In contrast, a decentralized multilevel system provides control and surveillance function in a distributed fashion, with hardware configured in a hierarchical manner. Available hardware is shifting emphasis to the use of distributed control system concepts.

Freeway Control Concepts. Control concepts for freeways are presented in the following three major areas:

- Ramp control
- Mainline control

- Corridor control and surveillance

Entrance ramp metering is the most widely used form of freeway traffic control. The Handbook provides a description of the techniques, factors governing application, and experiences with multiple levels of ramp control, such as:

- Closure
- Pretimed metering
- Traffic-responsive metering
- Merge control
- Integrated ramp control

An acceptance of metering has led to the use of on-freeway mainline control. Although there are examples of mainline metering, such mainline control has predominantly taken the form of driver information systems, variable-speed control, lane control, and reversible lane control. The integration of all the control elements within a freeway corridor, including surface streets, has led to the development of corridor control concepts. Each of these elements of mainline and corridor control is examined in the Handbook.

The broad area of surveillance as a control measure is also included. Incident detection and removal are other key concepts addressed in the Handbook.

Hardware

Chapters 5 through 9 of the Handbook provide expanded descriptions of state-of-the-art hardware elements for control systems, including the following:

- Detectors
- Local controllers
- System masters
- Communications
- Driver information systems

In each of these areas, emphasis is placed on the available state-of-the-art hardware made possible by the use of microprocessors.

System Selection

Selection of a system *appropriate* for the specific needs of a particular agency requires the use of a *process* which encourages the objective consideration of alternatives in a structured rather than a subjective manner. Chapter 10 of the Handbook describes a selection process which focuses on a practical approach meeting the requirements for Federal-aid funding. The approach has application, regardless of funding source, because it encourages a sense of commitment to the choice among participating agencies, individuals, and disciplines which contribute to successful implementation. This commitment and a full understanding of the requirements for operation and maintenance are considered vital.

Design and Implementation

The emphasis of Chapter 11 on Design and Implementation is toward successful system procurement. Practical problems, such as contractor prequalification and selection, definition of deliverable services, acceptance testing, data base development, and other identified pitfalls, are described along with suggestions for approaches to avoid such pitfalls. The system procurement approaches of a systems manager and/or an engineer/contractor are examined in detail. Use of a 2-step variation of the procurement approach is also described.

System Management

The final phase of the traffic control systems engineering approach covered in Chapter 12 has been termed management. This phase is concerned with the day-to-day operation of an implemented traffic control system in a real-world environment. This discussion is based upon the concept that a traffic control system must be envisioned as more than just a hardware system. One must consider the system's extension into the areas of personnel and organizational structure and be concerned that there are technical and managerial skills available to assure that the full capability of the control system can be realized and maintained over time.

SUMMARY

This Executive Summary briefly outlines the contents of an updated version of the *Traffic Control Systems Handbook* developed by the U.S. Department of Transportation, Federal Highway Administration.

REFERENCES

1. Wagner, Frederick A. *Overview of the Impacts and Costs of Traffic Control System Improvements* . Prepared for the Federal Highway Administration, Office of Highway Planning, March 1980.

XVI

TRAFFIC
CONTROL
SYSTEMS
HANDBOOK

XVII

Technical Report Documentation Page

1. Report No. FHWA-IP-85-11	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Traffic Control Systems Handbook
Revised Edition - 1985

5. Report Date
April 1985

6. Performing Organization Code

8. Performing Organization Report No.

7. Author(s)
R. Wilshire, R. Black, R. Grochoske, J. Higinbotham

9. Performing Organization Name and Address

PAWA-Winkelmann and Associates, Inc.
12660 Coit Road
Dallas, TX 75251

10. Work Unit No. (TRAIS)
32ZQ 918

11. Contract or Grant No.
DOT-FH-61-83-C-00007

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
Office of Implementation
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report
February 1983 - April 1985

14. Sponsoring Agency Code

15. Supplementary Notes

FHWA Contract Manager: Charles R. Stockfisch, HRT-20

16. Abstract

Within the broad spectrum of transportation systems management (TSM), traffic control systems play a key role in the efficient operation of urban streets and freeways. In the mid-1970s, FHWA published the original *Traffic Control Systems Handbook* as a compendium of available technology and practice. In the intervening years, control systems technology and hardware advances, permitted by the application of the microprocessor, have contributed to widespread use of such systems.

This revision retains much of the valuable material and basic scope of the original Handbook, but updates discussions of concepts and hardware to reflect current state of the art. Further, it is focused toward the more experienced signal and control systems designer and user, with discussions of actual experience and pitfalls. Topics addressed in the Handbook include:

- Available systems technology
- Control concepts — urban streets
- Control concepts — freeways
- Detectors
- Local controllers
- System masters
- Communications
- Driver information systems
- Selection of a system
- Design and implementation
- System management

17. Key Words

Communications
Controller assemblies
Control system masters
Control systems
Detectors
Freeway management
Freeway operations
Incident detection
Ramp metering
Surveillance and control

18. Distribution Statement

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 456	22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

1. INTRODUCTION

CONTENTS

Section *Page*

1.1 HANDBOOK SCOPE AND OBJECTIVES 1.3

1.2 ROLE AND IMPACT OF TRAFFIC SIGNAL SYSTEMS 1.3

1.3 TRANSPORTATION SYSTEMS MANAGEMENT (TSM) RELATIONSHIP 1.4

1.4 BACKGROUND OF SYSTEM DEVELOPMENT 1.4
  Urban Streets 1.4
  Freeways 1.5

1.5 PRESENT STATUS — TRAFFIC SURVEILLANCE AND CONTROL SYSTEMS 1.6

1.6 HOW TO USE THIS HANDBOOK 1.6

REFERENCES 1.6

TRAFFIC
CONTROL
SYSTEMS
HANDBOOK

1. INTRODUCTION

1.1 HANDBOOK SCOPE AND OBJECTIVES

In the mid-1970s, the Federal Highway Administration developed and published the *Traffic Control Systems Handbook* to present basic technology used in planning, designing, and implementing traffic surveillance and control systems for urban street and freeway applications. This publication arrived on the scene during a period of rapid technological advances, both in control concepts and hardware, and presented a basic compendium of applicable technology, concepts, and practice in the traffic control field. Because of its timeliness, the Handbook was useful in fostering understanding and acceptance of such systems and preceded accelerated implementation and utilization of proven advances in traffic surveillance and control.

From its inception, the Handbook was targeted to a wide range of potential users — administrators, roadway designers, and newly assigned as well as experienced traffic operations engineers.

This updated version of the *Traffic Control Systems Handbook* has been developed with two overall purposes:

- To retain valuable material and basic scope of the original Handbook, but update discussions of concepts and equipment to reflect the current state of the art — Specifically, the revised Handbook deals with the microprocessor revolution and advances in control technology and real-world applications experiences.
- To focus the Handbook toward a more experienced user — For this reason, much of the tutorial material dealing with traffic studies, basics of data communications, and introduction to computers has been eliminated or relegated to a reference position.

Even with these shifts, the major specific objectives of this updated version of the *Traffic Control Systems Handbook* remain as follows:

- Provide a compendium of existing traffic control system technology
- Facilitate the understanding of the basic elements of traffic control systems
- Aid the understanding and application of new technology (such as computers and communications) to the traffic control field
- Broaden the viewpoint of the field of traffic control
- Serve as a basic reference to aid the practicing traffic engineer in planning, designing, and implementing new and effective traffic control systems
- Serve as a training aid in the field of traffic control systems

It is hoped that the reader will find these overall purposes and objectives successfully accomplished in the following sections of the Handbook.

1.2 ROLE AND IMPACT OF TRAFFIC SIGNAL SYSTEMS

No other device has such a daily impact on virtually every citizen as does the common, ever-present traffic signal. The trip to work is punctuated by stops at traffic signals, even on uncongested routes. School children obediently wait for the traffic signal to interrupt traffic so they can cross a busy thoroughfare. Drivers place their physical safety and that of their passengers confidently in the signal's ability to give them the right-of-way.

A signal's necessity is accepted by the citizen, and in fact demanded in some cases, to assure safety and mobility. The same citizen quietly assumes that the operating agency knows how to best operate the signals, and reluctantly reports only the most obvious failures. Inefficient operation annoys some but produces no ground swell of public reaction, even though such operation is silently stealing dollars from the user's pocket in increased fuel costs, longer trip times, etc. In the user's view, the signals are working and if they are suboptimal, it becomes a concern but not a crisis.

Research and actual application have demonstrated the effectiveness of signal system improvements in reducing delays, stops, fuel consumption, vehicle emission of pollutants, etc. A recent overview analysis of the impacts of traffic control system improvements prepared for the Federal Highway Administration (FHWA) Office of Planning states:

> The systematic *optimization of signal timing plans* in any type of signal system, regardless of the degree of advancement inherent in the master control system, is an essential continuing element of traffic control system management. Evaluation data from a variety of types of signal systems indicate that optimization of signal timing plans, carried out without necessitating any hardware modifications, results in an average *project level* improvement in speed or travel time of *12 percent* (*1*).

The report further indicates that each dollar spent in signal timing optimization yields 36 to 48 reduced hours of vehicle operation — making it the most cost-effective measure observed. Having signal equipment that makes such frequent timing changes possible and reasonably easy then becomes very important.

1.3 TRANSPORTATION SYSTEMS MANAGEMENT (TSM) RELATIONSHIP

Most U.S. cities are served by a well-planned, highly developed system of streets, highways, freeways, and some form of public transportation facilities. Because of past and continuing efforts to provide such physical and operational facilities, each city enjoys a high level of mobility and transportation access. Growth in traffic demand, however, always seems to outpace the ability to provide new or expanded facilities and service. This pressure places great emphasis on *operational* and *management* improvements in order to "get the most out of existing facilities." These actions have been labeled as Transportation Systems Management (TSM) activities.

The wide spectrum of TSM actions being implemented throughout the country include the following (*2*):

- Improved vehicular flow measures
- Preferential treatment of high-occupancy vehicles
- Reduced peak period travel
- Parking management
- Promotion of nonauto and high-occupancy auto use
- Transit and paratransit service improvements

The critical point to be made is that almost all of the activities planned as TSM measures impact or depend on the efficient and effective use of traffic signal systems. For example, efforts to promote and develop carpools are reduced in effectiveness when those carpools are delayed unnecessarily by poorly operated signals; or, the surface operation of transit in downtown is directly impacted by signal system operation. Traffic signal systems then are critical to the operational effectiveness of multimodal transportation facilities.

1.4 BACKGROUND OF SYSTEM DEVELOPMENT

Urban Streets

The development of traffic control systems for urban streets has paralleled the development and use of the automobile. It was after World War I, when the growth in automobile traffic became so rapid, that the police, who were responsible for handling traffic matters in the past, were overwhelmed as they realized their impotence in dealing with the problem. For its foundation, a traffic control system depends to a great extent on the technology of signaling systems developed for railroads. Today, in typical urban areas, approximately two-thirds of all vehicle-miles of travel, and even a higher percent of vehicle-hours of travel, are on facilities controlled by traffic signals (*1*). The quality of traffic signal operation, therefore, is a major determinant of urban vehicular traffic flow quality.

The first electric traffic signal in the United States was installed in Cleveland, Ohio, in 1914 (*3*). This was followed by the introduction of interconnected signal systems in Salt Lake City in 1917, where 6 intersections were manually controlled as a single system (*4*). In 1922, in Houston, Texas, 12 intersections were controlled as a simultaneous system from a central traffic tower. This system was unique in that it used an electric, automatic timer.

Six years later, in 1928, a flexible-progressive pretimed system was introduced. These pretimed systems were quickly accepted, and widespread installation followed until they were common in virtually every city in the United States. It could be speculated that their success was the result of their simplicity (almost any electrician could understand them), their reliability (rugged components were used, so that, with minimum maintenance, they could be installed and forgotten), and their relatively low cost.

It was recognized, however, that the early pretimed systems had limited flexibility. They could respond to traffic changes only as well as their operator could predict them and preset the systems to change on a time-clock basis. But predicting traffic conditions was difficult because of the efforts needed for data collection. Timing changes usually were avoided because of the time required to go to each local intersection controller and make a change.

Traffic-actuated local controllers using pressure detectors became available during the period 1928-1930. The controllers were a first step toward traffic-actuated control, but were only applicable to isolated intersections.

As a step toward advancing the state of the art of traffic control systems, an analog computer control system was developed and installed in Denver, Colorado, in 1952. This system attempted to apply some of the concepts of actuated isolated intersection control to signalized networks. Sampling detectors were used to input traffic flow data, and the system was designed to adjust its timing on a demand rather than time-of-day (TOD) basis. Over 100 of this type of system were installed in the United States in the 10-year period 1952-1962.

In 1960, a pilot study was conducted in Toronto using a digital computer to perform the centralized control functions (*5*). A fortunate by-product of this study was the amount of surveillance data made available by this form of control. While the computer used for the test was archaic by today's standards — an IBM 650 computer with about 2,000 words of drum memory — this control system approach was so encouraging that Toronto proceeded with a full-scale implementation, placing 20 intersections under computer control in 1963, and later expanding to a system of 885 intersections by 1973.

International Business Machines (IBM) began a cooperative development in 1964 with the City of San Jose, California, to further develop a computer traffic control system (*6*). An IBM 1710 computer was used for this development work. Control concepts developed and implemented in this project proved to be successful in significantly reducing stops, delays, and accidents.

Beginning in 1965, the City of Wichita Falls, Texas, contracted for the delivery of an IBM 1800 process-control computer to be used for traffic control. This traffic control system was placed in daily operation in October, 1966, controlling 56 intersections in the central business district. This system was later expanded to include 78 intersections. San Jose, California, shortly thereafter made a transition to the use of an IBM 1800 computer, and similar systems were installed in Austin and Garland, Texas; Portland, Oregon; Fort Wayne, Indiana; New York City; and Baltimore, Maryland. In these systems, traffic signals were controlled by using stored timing plans that were developed offline.

In 1967, the United States Department of Transportation (DOT), Federal Highway Administration (FHWA), began the development of the Urban Traffic Control Systems (UTCS) Project. The system was installed in Washington, D.C., and was used to develop, test, and evaluate advanced traffic control strategies (*7*). The system, which was completed in 1972, contained 512 vehicle detectors whose outputs were used to determine signal timing at 200 intersections. Extensive data processing, communications, and display capabilities were made available to support the traffic control strategy research. Later research efforts produced the Extended and Enhanced versions of the software package that implemented these concepts.

During the 1970s, over 300 computer-controlled signal systems were installed throughout the world. As computer hardware became smaller, faster, and less costly, the use of traffic-responsive control for street networks and arterials became more prevalent. Examples of the European traffic-responsive control systems include those installed in Glasgow, England; Toulouse, France; and Madrid, Spain. In the United States, traffic-responsive control systems were set up in several cities such as Los Angeles, California; Boulder, Colorado; Albany, New York; and Overland Park, Kansas.

In the 1970s, there was also continuing research and development of software packages and models for use with digital computer and microprocessor-based traffic control systems. The continuing developments in control hardware which incorporated solid-state devices and integrated circuits created a need for uniformity and standardization of control equipment.

The experience gained during the 1970s has shown that there is substantial room for improvement through control system application efficiency and by aggressive traffic signal operational management in order to minimize travel delays, stops, fuel consumption, and vehicle emissions. It has likewise been demonstrated that the existence of a computer-based traffic control system is no assurance that the street network is being operated in an efficient manner unless high priority is placed on systematically deriving and frequently updating the timing plans to optimize traffic flow.

Freeways

In urban street systems, considerable control experience has been developed throughout the period from 1917 to the present. This was not the case for freeways since they were originally conceived and designed as free-flowing, limited-access facilities with little advance consideration given to the possibility of needing control systems. Ever-increasing traffic demands and the resultant congestion, however, has forced attention on methods of improving freeway flow through traffic surveillance and control. In California, Illinois, Michigan, and Texas, several pioneering studies (*8-13*) were performed to investigate ways to improve freeway operation. This work, initiated in the early 1950s, led to the increased usage of freeway surveillance and control.

From a research and development point of view, the work on freeway surveillance and control systems has progressed rapidly. The various studies and experiments in this field produced new concepts of control and introduced new applications of advanced control equipment in the form of closed-circuit television, communication and electronic components, and advanced digital computers.

1.5 PRESENT STATUS — TRAFFIC SURVEILLANCE AND CONTROL SYSTEMS

The brief period of the late 1970s and early 1980s has witnessed widespread acceptance and implementation of advanced traffic surveillance and control systems — for both freeways and urban street systems. Use of the digital computer has become the accepted way to implement on-street control. Such acceptance has been accelerated by the revolutionary advances, and associated cost reductions, in computer and electronic technology. The microprocessor has been a strong factor in this progress in that its use in local controllers has virtually removed any operational constraint previously imposed by hardware capability. Today, the constraints imposed on effective system operation are the product of the ability of the control systems engineer operating within a sometimes restrictive jurisdictional framework, often lacking sufficient funds for system implementation or operation.

Present action within the field of traffic surveillance and control has advanced beyond experimentation to the point where such systems are considered effective tools of operation. Basic control concepts have been refined through the experiences of multiple users. An effective network of system designers, manufacturers, and suppliers exists to offer choices in system selection. The cooperative participation of governmental agencies (Federal, state, local) and commercial and professional organizations (manufacturers, consultants) continues in the development efforts of hardware and software. A prime example has been the development of the Model 170 controller unit.

1.6 HOW TO USE THIS HANDBOOK

This *Traffic Control Systems Handbook* retains the basic systems engineering organizational format used in the original publication. In the Table of Contents, it can be noted that the material covered deals progressively with control concepts, individual hardware elements, guidance on how to select and implement the selected system, and finally a discussion of ongoing system management.

The casual reader interested in a brief overview, as well as all Handbook users, is encouraged to read Chapter 2 first. In this chapter, Available Control Systems Technology, overview information is provided concerning equipment and control concepts, along with discussions of key jurisdictional factors to consider in the search for an appropriate solution. Here, the importance of a commitment to maintenance and staffing for achieving successful operation is emphasized.

For detailed discussions of individual equipment elements, the reader is directed to Chapters 5 through 9. Chapter 10 presents system selection guidelines which embody the essence of FHWA policy and a utility/cost approach. The emphasis of Chapter 11, Design and Implementation, is toward successful system procurement — approaches used and pitfalls encountered. It also includes material on deliverable services and acceptance testing. Chapter 12, System Management, addresses system operation, maintenance, and evaluation. This chapter further provides material on staffing for maintenance and operation, plus day-to-day operations procedures. The traffic management team concept is also presented, along with new material on reported system benefits.

REFERENCES

1. Wagner, Frederick A. *Overview of the Impacts and Costs of Traffic Control System Improvements.* Prepared for the Federal Highway Administration Office of Highway Planning, March 1980.
2. Roark, John J. *Experiences in Transportation System Management.* NCHRP Synthesis of Highway Practice No. 81, Transportation Research Board. Prepared by PAWA, Inc., November 1981.
3. Mueller, Edward A. "The Transportation Profession in the Bicentennial Year — Part II." *Traffic Engineering,* Vol. 46, No. 9, 1976, pp. 29-34.
4. Sessions, Gordon M. *Traffic Devices — Historical Aspects Thereof.* Institute of Traffic Engineers, Washington, D.C., 1971.
5. Irwin, Neal A. "The Toronto Computer-Controlled Traffic Signal System." In *Traffic Control Theory and Instrumentation.* Plenun Press, New York, 1965. (See also: Casciato, L., and S. Cass. "Pilot Study of the Automatic Control of Traffic Signals by a General Purpose Electric Computer." *Highway Research Board Bulletin 338,* 1962.)

6. International Business Machines Corporation. *San Jose Traffic Control Study*. IBM Corp., March 1965. (Initial Report.)
7. Federal Highway Administration. *The Urban Traffic Control System in Washington, D.C.* U.S. Department of Transportation, Washington, D.C. (Undated information Brochure.)
8. Moskowitz, K. "Research on Operating Characteristics of Freeways." *Institute of Traffic Engineers Proceedings.* 26th Annual Meeting, San Francisco, September 25-27, 1956, pp. 85-110.
9. Keese, C. J.; Charles Pinnell; and W. R. McCasland. "A Study of Freeway Traffic Operation." *Highway Research Board Bulletin 235*, 1960, pp. 73-132.
10. May, Adolf D., Jr. "Experimentation with Manual and Automatic Ramp Control." *Highway Research Record 59*, 1964, pp. 9-38.
11. Gervais, E. F. "Optimization of Freeway Traffic by Ramp Control." *Highway Research Record 59*, 1964.
12. Wattleworth, J. A., and D. S. Berry. "Peak-Period Control of a Freeway System — Some Theoretical Investigations." *Highway Research Record 89*, 1965, pp. 1-25.
13. Drew, D. R. *A Study of Freeway Traffic Congestion.* Texas A&M University, College Station, Texas, 1964. (Doctoral Dissertation.)

2. AVAILABLE CONTROL SYSTEMS TECHNOLOGY

CONTENTS

Section *Page*

2.1 INTRODUCTION 2.3

2.2 CONTROL SYSTEM FUNCTIONS 2.3
- **Data Gathering** 2.3
- **Decision-Making** 2.3
- **Execution** 2.3
- **Verification** 2.4
- **Evaluation** 2.4
- **Traffic Control Relationship** 2.4

2.3 RANGE OF AGENCY NEEDS 2.4

2.4 RANGE OF AVAILABLE OPTIONS 2.5
- **Transportation Systems Management (TSM) Relationship** 2.5
- **Control System Options** 2.6
  - ***Basic System*** 2.6
  - ***Mid-Range System*** 2.6
  - ***Sophisticated Systems*** 2.6
- **Criteria for Selection** 2.7

2.5 AVAILABLE TECHNOLOGY 2.7
- **Hardware** 2.7
  - ***Detectors*** 2.7
  - ***Local Controllers*** 2.7
  - ***System Masters*** 2.7
  - ***Communications*** 2.9
  - ***Display*** 2.9
- **Software** 2.10
  - ***Real-Time Control*** 2.10
  - ***Optimization and Timing Plan Development*** 2.10
  - ***Simulation*** 2.10

2.6 A LOOK TO THE FUTURE 2.10

REFERENCES 2.11

9

TRAFFIC
CONTROL
SYSTEMS
HANDBOOK

2. AVAILABLE CONTROL SYSTEMS TECHNOLOGY

2.1 INTRODUCTION

Significant advances have been made in traffic control systems technology during the past decade primarily as a result of the microprocessor and associated revolutionary advances in electronics. Concentrated research and widespread user experience have also advanced the state of the art. Today, agencies with responsibility for traffic control systems are offered a wide range of choices with respect to hardware and operational features, many of which are implemented through software.

A major objective of this Handbook is to assist users in defining, evaluating, and selecting systems which match their needs. In this chapter, a broad overview of system functions and available options for both hardware and software is presented. Also, attention is focused on the factors to be considered in system selection which can lead to successful system operation.

2.2 CONTROL SYSTEM FUNCTIONS

Traffic control systems may be equated in many ways to industrial process control systems in that some portion of the process is controlled in real time within restrictive limits to produce an optimum (or consistent) product. For traffic control, that product may be the optimum allocation of right-of-way among competing demands within a group of signalized intersections, or it may be a response to some exception-type condition. Both industrial process control and traffic control systems exercise their control in a cycle (or closed-loop) manner as shown in Figure 2.1, closing the loop of control functions within a short time period. These control system functions may be compared to traffic control system functions as follows.

Data Gathering

Traffic flow data on volume, lane occupancy, and speed may be gathered from detectors located to provide intersection-specific and/or system-sampling data. Preemption data, such as for railroad crossings or emergency-vehicle routes, may also be gathered along with other hardware status-type data.

Decision-Making

On the basis of some specified analysis of traffic data collected, the control system will decide that a specific response is appropriate for dealing with the conditions observed. That choice could be based on something as simple as time-of-day (TOD), or a more sophisticated analysis based on a comparison of the smoothed weighted average of volume and lane occupancy for a variable combination of detectors within multiple subsystems, with opportunities for exception condition overrides. The decision-making ability of traffic control systems is one area where significant expanded capability has been provided by the application of the microprocessor-based digital computer.

Execution

Control decisions for traffic control must be executed through control equipment to drive the red-yellow-green signal indications to which motorists respond. In simplified form, a control system master directs local controller units to display signal indications in some particular sequence of intervals and in a manner which coordinates traffic flow within a related area. This control may be exercised through coordinating commands which essentially say, "Do this until I tell you differently," or through controlling commands which say, "OK, do this; now do that." Controls of the latter type were characteristic of earlier centralized interval command systems which concentrated the systems' computational and decision ability within the master. The use of distributed

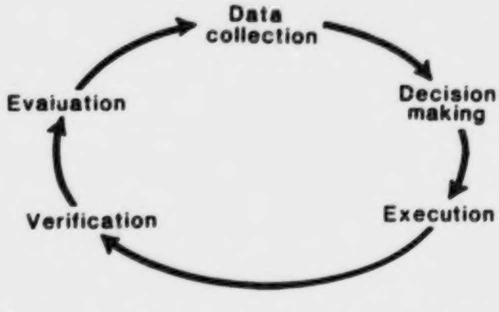


Figure 2.1. Basic functions of a traffic control system

11

BEST COPY AVAILABLE

intelligence in newer systems has permitted execution of control through downline loading of timing plans, preprocessing of detector data, and other techniques permitted by having system intelligence at the local intersection.

Verification

Followup to ensure that control decisions based on the best possible data get executed as intended constitutes the verification, or surveillance, function. Verification may include hardware monitoring to see if the local controller unit is actually displaying the intended signal interval at the appropriate time, or it may also include reasonableness checks or visual confirmation of traffic data collected.

Evaluation

Evaluation is not only the final step in the process control system loop; it is also the beginning of the next cycle through the loop. Performance evaluation of control through an analysis of surveillance data on measures of effectiveness (MOE), such as percentage stops, vehicle-seconds delay, etc., defines the level of improvement or the degradation of the system's performance (or product). Such evaluation thus provides a basis, when coupled with new data, for the next cycle through the process control loop.

Traffic Control Relationship

How does this process control loop relate to traffic control in an historical perspective? First, traffic control is a closed-loop process. But in the early pretimed systems, the loop took a long time to close because it entailed an extended series of discrete operations. For example, data gathering was by manual means external to the control system; decision-making was on a fairly flexible time-of-day (TOD), day-of-week (DOW) basis; execution was by one-way electrical commands over multiwire cable; verification depended on infrequent observation and motorist complaints; and any evaluation was an expensive, labor-intensive field data collection effort that was generally not even done. While the result of these was a product of sorts that may have been relatively consistent, it was extremely inefficient or suboptimal.

Today, however, control systems have advanced to the point where the control loop may be closed on a cycle-by-cycle or short-period basis in real time — i.e., in time to do some good.

2.3 RANGE OF AGENCY NEEDS

Although each agency with responsibility for traffic control systems represents a unique entity with no two exactly alike, there are many individual similarities such as the following:

- Area of responsibility — Freeway control systems are generally installed, operated, and maintained by state highway departments, whereas urban street systems are the responsibility of the local jurisdiction (city/county). Some agencies may have dual responsibilities.
- System type — A freeway control system with ramp metering, incident detection, and video surveillance is obviously different from a local arterial street signal system. Even on local streets, there are closed-network central business district (CBD) systems of closely spaced intersections, open- and closed-network arterial systems, diamond-interchange control systems, and isolated intersections. A single agency may have a need for a system (or systems) to encompass the full spectrum. However, it is more common for an agency's needs to be focused on one type of system.
- System size — Jurisdiction size is frequently considered as an indicator of the type of control system needed. On examination, it is easy to see that the control system needs of an isolated, stand-alone city with a population of 100,000 people are different from those of a predominantly residential suburban city of the same size. System size is a better way to categorize agency needs, because an arterial control system for 5-20 intersections is likely to be just as applicable in small or large cities.
- Existing hardware — In most jurisdictions, traffic control hardware represents an accumulation of different age equipment from multiple manufacturers, purchased over an extended time, using low-bid procurement techniques. Its current condition is greatly affected by the level of effort given to proper maintenance during its use. For example, though the hardware may be of such manufacture as to permit integration into a system, its physical condition and reliability may preclude its continued use.
- Special features needed — Individual jurisdictions may require special control capabilities for such features as railroad preemption, lane control signals, HOV lane control, peak-hour turn restrictions, and fire (or emergency vehicle) preemption. In addition, some locations may require extensive capabilities to accommodate special events, such as parades or major athletic events.

What are the conditions that focus attention on a need to install or upgrade traffic control systems? First, growth and/or changes in traffic demand create a need to examine the adequacy of existing traffic control systems. When traffic flows are well below available capacity and there is no recurrent congestion (or perception of congestion by the motorist), little public demand develops for control system improvement. However, as demand approaches capacity and congestion becomes evident, there is increased demand for, and a greater need of, improved control system operation. Although this is not to say that control system improvements should be postponed until congestion appears, rather it is recognized that the typical situation occurs where the provision of significant funding for major improvements generally follows public perception of need. Changes in traffic demand may also highlight the functional inadequacy of the existing control system. It should also be noted that, while traffic control systems *do not create capacity*, they can *provide a significant tool* for facilitating the full utilization of available capacity.

The second major condition which creates a need to upgrade traffic control systems is the frequent failure of older equipment, which results in degraded and inefficient on-street operation. Such malfunctions and maintainability problems may be the result of inadequate maintenance, continued operation of equipment that has exceeded its design life, poor quality of equipment from the start, and perhaps lack of spare parts and maintenance support resulting from business turbulence within the manufacturer community.

Nevertheless, the definition of traffic control system needs for a specific agency does not lend itself to a cookbook approach. Rather, it is a design process which requires the application of experience and detailed examinations of conditions, capabilities, desires, and commitments. This definition of what the system must do is an important element of a feasibility or predesign study. Further details of such studies are included in Chapter 10. Experience has shown that specific traffic control system objectives should be established in the following areas:

- Traffic operations — The ability to respond to existing and anticipated future traffic operations requirements. Specific objectives might be to obtain maximum efficiency in terms of minimum delay, minimum stops, and maximum capacity utilization consistent with the safety of operation.
- Reliability — Minimum control system downtime, minimum cost of maintenance, and maximum ability for automated detection and reporting of equipment failures.
- Adaptability — The ability to satisfy traffic operation requirements over a long period of time under changing conditions.
- Implementation — Ease of installation or changeover from an old system to a new one with minimum technical problems and disruption of traffic flow.
- Incidental benefits — Additional functions not necessarily related to real-time control which may be performed with no loss of primary function effectiveness, such as surveillance, traffic data collection and storage, and driver information system control.

2.4 RANGE OF AVAILABLE OPTIONS

Transportation Systems Management (TSM) Relationship

Since the concept was first introduced in the mid-1970s, transportation systems management (TSM) has evolved from a list of about 150 low-cost actions to a concept for the productive use of existing transportation resources through their coordinated operations and improved management. TSM has been recently defined as "a philosophy about planning, programming, implementation, and operations that calls for improving the efficiency and effectiveness of the transportation system by improving the operations and/or services provided" (*1*). TSM, then, is an umbrella philosophy whose goal is first to analyze the total system and then to improve its operation prior to capital-intensive projects which add significant capacity.

Roark classifies TSM actions within 9 different urban operating environments, including freeway corridor, arterial corridor, central business district (CBD), regional operating environment, neighborhood, major employment site (non-CBD), outlying commercial center, major activity center, and modal transfer point (*2*). In contrast, Wagner uses 2 primary categories — (1) *supply* strategies and (2) *demand* strategies (*3*). *Supply* strategies are those actions whose primary focus is on changing the *quality* of vehicular flow, whereas *demand*-oriented strategies include those actions intended to decrease the *quantity* of vehicular travel. Supply actions include arterial signal coordination, signal removal or flashing, right turn on red (RTOR), freeway surveillance, incident management, parking prohibition, turn controls, and bottleneck-removal programs. Carpools, vanpools, high occupancy vehicle (HOV) priority treatments, and variable work hours are actions that fit the demand category.

In both classification schemes, traffic control systems and their effective operation are prominent measures which affect TSM and, as such, are vital to the realization of the full potential of several other TSM actions. For example, it does little good to entice drivers to ride the bus or join a vanpool if *all* vehicles (including buses and vans) are stopped and/or delayed by inefficiently operating traffic signals.

Control System Options

Since traffic control systems are such a key element in achieving improved transportation service from available roadways and freeways, what range of options is available? Although system sizes may range from two to several hundred intersections, it has been found that the number of intersections itself bears little relationship to the sophistication of the system (*4*). Therefore, the degree of sophistication is used to define a spectrum of systems, with the following representing the extremes and midpoint of this spectrum.

Basic System. The system was conceived by the Traffic Control Committee of the Transportation Research Board as a stand-alone system with malfunction detection, centralized timing plan installation, and simplified operator interface (*4*). This system emerged as a concept which provides a scaled-down system with the ability to accept either the addition of modular features as required or expansion at a later time. Its key features include the following (*4*):

- The system should control local intersections from a central site — The central site should have, as a minimum, a mini- or microcomputer, a disk for additional memory, a console typewriter, and a CRT.
- Timing plans should be selected on a time-of-day (TOD), day-of-week (DOW), week-of-year basis.
- The system should provide malfunction-detection capability.
- The system should operate on a 24-hr-a-day basis, unattended, with operator attention required only periodically.
- Timing plans must be updatable from the central site. Specific features should include: (1) timing plans not installed while the system is online; (2) plans generated and stored in the background mode while the system is online and then installed when the system is offline; and (3) limited fine-tuning capability when the system is on line, with any fine-tuned changes to be made permanent in the offline mode.
- The system should be expandable to incorporate additional features and to add additional intersections without requiring a large investment in central equipment.
- The entire system should be user-friendly, using prompting messages which can be inhibited by the experienced operator; provide offline software to help in identifying the need for new timing plans, as well as processing detector data to support development of new plans; and provide performance reports, including the possible use of dynamic displays.
- The system should provide enhanced maintainability through a self-diagnostic capability, with fewer boards as well as minimized preventative maintenance, self-training course availability, and standardized documentation symbols.

The following are features not included in the basic system, but items which should be available as options:

- Traffic-responsive decision logic and data input
- Measures-of-effectiveness computation and evaluation
- Display maps, either a standard dynamic wall map or a TV projection of such a map

In terms of system architecture, the basic system could consist of local controllers in direct communication with a central master, or a zonal master could be inserted between the two.

Mid-Range System. A mid-range system was described by Christenson, et al. (*4*) for those agencies whose resources and abilities might classify them as candidates for a more sophisticated control system. In comparison to the basic system, the following additional features would be included (*4*):

- Storage and implementation of different signal plans
- Preemption capability
- Traffic-responsive timing and signal plan selection

Optional features might include the following:

- Multiple levels of surveillance for traffic-responsive operation and for other purposes
- Online timing plan computation (or construction) and traffic pattern prediction
- A more sophisticated timing plan evaluation methodology

Implementation of the mid-range system could take several forms depending on agency preferences and communications factors. Both centralized and decentralized systems could fit this category.

Sophisticated Systems. Signal systems which have been custom designed for a specific installation and which provide advanced control logic and capabilities, can be classified as sophisticated systems. Today, they would typically include the following:

- Utilize dynamic wall-map displays or projection-type displays
- Make use of online pattern-matching traffic-responsive techniques
- Have extensive surveillance capability
- Provide detailed reporting of system MOE's and equipment performance through an elaborate data base management capability
- Be monitored (or staffed) on a full-time basis

Special controls for transit vehicles and real-time displays of driver information would also be provided in the sophisticated system. Its configuration could be either of a centralized or decentralized architecture. However, large systems would be more likely to adopt the hierarchical approach where portions of the system are controlled by decentralized regional, zonal, or subsystem masters, and require higher levels of maintenance and operation effort.

Table 2.1 summarizes the functions and features of traffic control systems and gives insights into the way they might be included in each of the three systems — basic, mid-range, and sophisticated (*4*).

Criteria for Selection

The above discussion emphasizes that a wide range of alternative systems is available to meet the traffic control system needs of a jurisdiction. Making the most appropriate selection requires critical self-examination and consideration of life-cycle issues pertaining to system acquisition. In other words, just because City A selected a sophisticated system is not an adequate reason for City B to automatically follow suit.

Matching a control system's capabilities to a set of *identified* agency requirements is perhaps the most crucial element of the system selection process. It is obvious that a system that will not do what must be done is not really a viable candidate for selection. Likewise, care must be taken not to over-buy system capabilities which may not be applicable or be used. Unused capability usually results in both unnecessarily high first cost and subsequent operating costs.

Care must be taken also to match the sophistication of the system to the anticipated ability of the staff to operate and maintain its components. Likewise, there must be a demonstrated commitment to the ongoing costs of staffing and maintenance to assure system success. As described in new Federal regulations (see Chapter 10 and Appendix A), the availability of funds to procure traffic control systems must be matched by a similar commitment to provide adequate resources for operation and maintenance.

Chapter 10 provides a more detailed discussion of a suggested system selection process which utilizes an effectiveness-analysis approach. It also includes a description of the utility/cost analysis approach.

2.5 AVAILABLE TECHNOLOGY

Available control system technology has progressed over the past few years to the point where current hardware and software capabilities no longer constrain system configuration or application of appropriate control concepts. The contemporary transportation engineer or control system designer now has a wide array of hardware and software options from which to choose in defining alternative control systems. The challenge is to use them effectively in achieving improved on-street traffic performance.

Hardware

The following chapters in this Handbook describe in depth the various hardware elements of a control system. The following discussion is therefore limited to overview descriptions of available system hardware.

Detectors. For control system use, the loop detector has proved to be a reliable choice, capable of providing traffic data on vehicle presence which can be manipulated to give flow measurements of volume, lane occupancy, speed, stops, and delays. In application, problems with their use are attributable more to the care and adequacy of pavement loop installation than to electronics malfunctions. Chapter 5 provides information on installation and configuration for system detectors.

Local Controllers. Almost all new local controller units are microprocessor-based "smart" devices which offer extensive and flexible ability for control. Generally provided also are features which enhance their ability to be integrated into systems. In Chapter 6, two basic local controller approaches are described — the Model 170 controller unit developed by California and New York, and the industry-standard NEMA controller unit. Under both approaches, great strides have been made in developing interchangeability among manufacturers, and in improving reliability and maintainability. The chapter also includes discussion of the application of pretimed controllers.

System Masters. Time-based coordinators represent the low end of the scale of system coordination,

15

Table 2.1 Control systems functions and features

Functions/Features	Basic			Mid-Range			Sophisticated		
	R	O	Where	R	O	Where	R	O	Where
Features that define the signal plan and the timing plan									
● Provide for storage of several different signal plans	-	-	-		x	I.Z.R.C	x		I.Z.R.C
● Provide for implementation of different signal plans	-	-	-		x	I.Z.R.C	x		I.Z.R.C
● Provide for storage of many different timing plans	x		I.Z.C	x		I.Z.R.C	x		I.Z.R.C
● Provide a transition timing strategy	U		I.Z.C	x		I.Z.R.C	x		I.Z.R.C
● Provide a differing signal plan and timing strategies under preemption conditions	-	-		x		I.Z.R.C	x		I.Z.R.C
● Provide for implementing many different timing plans	x		I.Z.C	x		I.Z.R.C	x		I.C.R.C
Features that have to do with timing and signal plan selection									
● Provide for manual timing and signal plan selection	x		Z.C	x		Z.R.C	x		Z.R.C
● Provide for time-of-day timing and signal plan selection	x		Z.C	x		Z.R.C	x		Z.R.C
● Provide for traffic-responsive timing and signal plan selection		x	Z.C	x		Z.R.C	x		Z.R.C
● Provide for determination and storage of timing and signal plan selection parameters	x		Z.C	x		Z.R.C	x		Z.R.C
Features that have to with operational modes									
● Provide for pretimed controller operation	U			x		I.Z.R.C	x		I.Z.R.C
● Provide for actuated controller operation	U			x		I.Z.R.C	x		I.Z.R.C
● Provide for free operation	U			x		I.Z.R.C	x		Z.R.C
● Provide for unattended operation	x		C	x		Z.R.C	x		Z.R.C
Features that have to do with time keeping									
● Time each interval for each signal	x		I.Z.C	x		I.Z.R.C	x		I.Z.R.C
● Maintain a low-precision time base (for interval timing)	x		I.Z.C	x		I.Z.R.C	x		I.Z.R.C
● Maintain a high-precision time base (for coordination timing)	x		I.Z.C	x		I.Z.R.C	x		I.Z.R.C
● Provide a backup timing system	U				x	I.Z.R.C		x	I.Z.R.C
Features that have to do with storage of ancillary data									
● Provide for storage of detector data		x	Z.C		x	Z.R.C	x		Z.R.C
● Provide for storage of system activity log	U		C	x		C	x		C
● Provide for storage of special events and their time	x		C	x		C	x		C
● Provide for storage of variable messages	-				x	Z.R.C		x	Z.R.C
Features that have to do with safe operation									
● Detect and neutralize unsafe signal displays	U			x		I	x		I
● Provide for flashing-signal operation	U			x		I	x		I
● Provide for manual override of signal display	U			x		I	x		I
● Provide smooth pickup, dropoff and reversion to/from standby	U			x		Z.R.C	x		Z.R.C
● Provide a logical fail-safe, restart ability	U			x		Z.R.C	x		Z.R.C
Features that have to do with detection									
● Monitor detection devices that indicate a demand for right-of-way service	U			x		I	x		I
● Determine the volume of vehicles passing a detector		x	I.Z.C		x	I.Z.R.C	x		I.Z.R.C
● Determine the percentage occupancy of vehicles near a detector		x	I.Z.C		x	I.Z.R.C	x		I.Z.R.C
● Determine individual vehicle speeds (speed trap)				x	Z.R.C	x		Z.R.C	
● Determine measures of effectiveness		x	Z.C		x	Z.R.C	x		Z.R.C
● Detect demand for service by emergency of mass transit vehicles	U				x	Z.R.C	x		Z.R.C
● Preprocess detector data		x	I		x	I.Z.R.C	x		I.Z.R.C
● Final-process detector data		x	Z.C		x	Z.R.C	x		Z.R.C
● Provide logic for ensuring system stability (hysteresis)		U	A.C		x	Z.R.C	x		Z.R.C
● Detect incidents					x	Z.R.C		x	Z.R.C
● Measure long-term traffic flow trends					x	C		x	C
● Classify vehicles by type					x	I		x	I
● Determine and use environmental conditions					x	Z.R.C		x	Z.R.C
Features that have to do with timing plan and signal plan computation									
● Compute timing plans and signal plans in background or off line	x		C	x		C	x		C
● Compute timing plans and signal plans on line					x	C		x	R.C
● Predict short-term flow trends					x	C	x		R.C
Features for maintenance and failures management									
● Detect and classify component failures and provide necessary alarms	x		Z.C	x		Z.R.C	x		Z.R.C

Table 2.1 Control systems functions and features (Continued)

Functions/Features	Basic			Mid-Range			Sophisticated		
	R	O	Where	R	O	Where	R	O	Where
Features that allow operator monitoring and control of the system									
• Provide a menu-driven operator instruction system	x		C	x		C	x		C
• Provide for an override of the menu-driven system for the experienced operator	x		C	x		C	x		C
• Provide for operator-supervised display subsystem	x		C	x		C	x		C
• Provide hard-copy reports	x		C	x		C	x		C
• Provide a wall-type map		x	C		x	C		x	C
• Provide a projection-TV map		x	C		x	C		x	C
• Provide a user-friendly database management system	U			x		C	x		C
• Provide a color-graphic CRT displays					x	C	x		C
Features that provide assistance for system and timing plan evaluation									
• Provide software and hardware to support timing plan and system evaluation procedures	x		C	x		C	x		C
Features which provide systemwide communications									
• Encode/decode data for communications up-loading/down-loading	x		I,Z,C	x		I,Z,R,C	x		I,Z,R,C
• Modulate/demodulate carrier frequency for communications over different media	x		I,Z,C	x		I,Z,R,C	x		I,Z,R,C
Features that define demarcation points									
• Provide utility power demarcation point	U			x		I	x		I
• Provide telephone or other communication system demarcation point	U			x		I	x		I
• Provide police manual override demarcation point	U			x		I	x		I

Definitions:
R = Required
O = Optional
Where = Location where function could be performed
I = Local intersection
Z = Zonal master
R = Regional master
C = Central master
U = Undefined, but assumed to be part of a BASIC system

Source: Reference (*4*)

which then increase in complexity to field-located, small system (arterial) masters, and finally to the large central computer master. In some systems, personal computers are being used as the control interface and display element. All of these various types of system masters and related hardware are described in Chapter 7.

Communications. One of the most expensive elements of the traffic control system is communications. Traditionally, a direct-wire path has been the preferred communications medium. Costs of providing direct-wire paths (either multiconductor or multipair cables) have grown so high they have forced a search for alternatives. One practical way to reduce the number of direct-wire paths needed is to multiplex data transmission and thereby increase the data-carrying capacity of a single wire or wire-pair. Today, typical systems use agency-owned multipair cables and time-division (TDM) and/or frequency-division (FDM) multiplexing. The use of leased telephone pairs has declined on the basis of user experienced problems and costs. Breakup of the telephone companies and deregulation with its impact on the uncertainty of rates have further reduced the consideration of using leased wire pairs.

The use of coaxial cable is receiving widespread interest because of the ability to transmit high data rates and video, and also because of its availability on a shared-use basis with cable TV in many areas. While the use of coaxial cable is considered to be state of the art, the use of fiber-optic cable in traffic control systems is considered still in the "pioneer stage." Its future use, however, is considered highly promising, as evidenced by its current use for trunk-line communications in the Los Angeles system.

These communication technologies are described in Chapter 8.

Display. The display of traffic flow data and system status has been a particularly difficult task. Tabulations of data on CRT's and printers are necessary and useful for system operators, but they are limited in providing areawide data displays. Large wall maps, with dynamic displays of traffic flows at various threshold levels, and system status displays fill the areawide needs, but they are expensive and difficult to maintain. Many system personnel consider them as only public relations devices rather than meaningful control system elements.

The recent application of computer color graphic displays coupled with large screen projection television, appears to be the state-of-the-art solution. Wide-area map-type displays can be created with the ability to focus on smaller areas with increasing levels of detailed information displayed. Displays can also be modified as conditions change, in contrast to the difficulty in modifying wall-map displays. Further, computer-generated graphic displays can be easily transmitted to remote locations for informational use, such as to dispatch centers, transportation administrative areas, and public display areas.

Software

Software used in traffic control systems is described in Chapters 3, 4, and 6. There, the reader will find discussions of real-time control (applications) software, timing plan optimization programs, and simulation programs.

Real-Time Control. At the local controller level, real-time control software has been developed to permit the controller unit to function as a signal switching unit, receiving detector inputs, processing status data, computing timing, and driving signal lamp load switches. Manufacturers of standard NEMA and pretimed controller units provide such software (or firmware) as a part of the device. By contrast, Model 170 software has been developed by both manufacturers and users.

For larger systems, the UTCS Enhanced software package has been developed with FHWA support as a very capable program using a high-level language to provide machine independence. The package has been acceptance-tested and demonstrated in two geographic locations (Broward County, Florida; and Birmingham, Alabama). Further use in other locations such as Los Angeles and San Diego, California, is operational. Similar large-system software packages have been developed and are available from systems houses, system contractors, and traffic signal manufacturers, such as Dallas, Texas, and Dade County, Florida.

Optimization and Timing Plan Development. Available programs for optimization and timing plan development are described in Chapter 3. These include the PASSER programs, TRANSYT, and SIGOP. PASSER II (84) is now available for arterial applications and has been adapted for use on microcomputers. TRANSYT-7F has been developed as an "Americanized" version and is widely used in developing optimized network timing plans. SIGOP III was released for use in early 1984. Training courses on the use of each have been developed by FHWA, and are available.

Simulation. Simulation models for use in urban street and freeway applications are described in Chapter 3 and 4. Included are CORQ-CORCON, the FREQ model family, INTRAS, MACK model family, NETSIM, SCOT, and others.

2.6 A LOOK TO THE FUTURE

The past decade has been marked by rapid advances in traffic control systems technology, as characterized by the development and widespread application of the microprocessor. In contrast, the next decade is seen as a *decade of application* — a period of assimilating recent advances and packaging them for widespread implementation. Small basic-type systems are likely to become the modular building block for application on arterial systems, in small jurisdictions, and as modular elements of hierarchical large systems. The challenging area of growth will probably encompass the area of systems management, including refined techniques for effective day-to-day operation and utilization.

Research activities have been drastically curtailed over the past three years. As a result, dramatic changes in the traffic control systems field are not to be anticipated in the immediate future. With reduced resources, research initiatives are expected to be limited to control concepts and strategies for saturated flow, networks of traffic-responsive (actuated) controls, and strategies related to traffic restraint.

In terms of opportunities for the future, perhaps one of the greatest needs and opportunities lies in the area of cooperation, such as:

- Freeway and urban street controls — Typically, different agencies have responsibility for the control of freeway and urban streets within a single urban area. Often, competing objectives can lead to flow turbulence and performance degradation. These systems are interdependent to the point that they should perhaps be controlled by joint integrated systems and staffs from a common location.
- Multijurisdiction system — In the large metropolitan areas, traffic flows on a regional basis without regard to jurisdictional boundaries. Certain economics of scale and operational benefits could be realized

by the installation of single control systems for multiple jurisdictions. Examples of such cooperation already exist in the Ottawa-Hull and Las Vegas area systems.

- Transit-highway coordination — Opportunities exist to coordinate the control system needs of transit and highway systems. For example, HOV lane controls, light-rail interface at street crossings, bus priority systems, and vehicle identification and location systems all use similar technologies which could realize cost reductions through coordinated design and implementation.

REFERENCES

1. *Urban Transportation Planning. Federal Register*, Vol. 46, 1981, pp. 5702-5719.

2. Roark, John J. *Experiences in Transportation System Management*. National Cooperative Highway Research Program Synthesis of Highway Practice 81. Transportation Research Board, Washington, D.C., November 1981.

3. Wagner, Frederick A. *Energy Impacts of Urban Transportation Improvements*. Institute of Transportation Engineers, August 1980.

4. Christenson, Edwin C.; Samuel W. Covert; and Donald W. Proctor. *Functional Specifications for Microcomputer-Based Signal System: System Functional Requirements*. Task B Report, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., July 1983.

20

3. CONTROL CONCEPTS — URBAN STREETS

CONTENTS

Section *Page*

3.1 INTRODUCTION 3.5

3.2 CONTROL VARIABLES 3.5
  Vehicle Presence 3.6
  Flow Rate 3.6
  Occupancy and Density 3.6
  Speed 3.6
  Headway 3.8
  Queue Length 3.8

3.3 SAMPLING 3.8

3.4 FILTERING AND SMOOTHING 3.9

3.5 TRAFFIC SIGNAL TIMING PARAMETERS 3.9

3.6 TRAFFIC SIGNAL PHASING 3.9
  Phasing Options 3.10
  Variable-Sequence Phasing (Skip Phasing) 3.10

3.7 ISOLATED INTERSECTIONS 3.11
  Pretimed Control 3.11
  Traffic-Actuated Control 3.11
    Minimum Green Interval 3.12
    Passage Time Interval 3.13
    Maximum Green Interval 3.14
  Basic Considerations 3.14
  Traffic Flow 3.14
  Intersection Timing Requirements 3.14
  Intersection Timing — Webster 3.15
    Optimum Settings 3.16
    Example 3.16
  Intersection Timing — Critical Movement Analysis 3.18
  Intersection Timing — Traffic-Actuated Control 3.19
  Intersection Timing — Other Considerations 3.19
  Intersection Timing — Available Computer Software 3.21
    SOAP-84 Model 3.21
    TEXAS Model 3.21

Section *Page*

3.8 ARTERIAL STREET CONTROL 3.22
Timing Plan Elements 3.22
Traffic Flow Variations 3.22
Timing Plan Development 3.24
Manual Techniques 3.24
Offline Computer Techniques 3.25
MAXBAND 3.25
PASSER II-(84) Model 3.25
AAP-85 3.26
Online Control Techniques 3.26
Isolated vs. System Control 3.27

3.9 CLOSED NETWORK CONTROL 3.28
Basic Concept 3.28
Preferential Control 3.28
Timing Plan Development 3.29
Manual Techniques 3.29
Computer Techniques 3.30
TRANSYT-7F Model 3.30
SIGOP-III Model 3.31
Experience with Offline Models 3.31
UTCS Control Techniques 3.32
First-Generation Control (1-GC) 3.32
Second-Generation Control (2-GC) 3.32
Third-Generation Control (3-GC) 3.33
UTCS First Generation Enhanced and Extended 3.33
UTCS 1½-Generation Control 3.35
FORCAST 3.35
Experience with Control Techniques 3.36
Simulation Models 3.38
NETSIM Model 3.38
NETSIM/BPS Model 3.39
TRANSYT-7F 3.39
Section Control 3.39
Section Configuration 3.40
Saturated Flow Conditions 3.40
Critical Intersection Control (CIC) 3.40
Network Saturation 3.41
Traffic Metering 3.41
Pedestrian Control 3.41

3.10 AREAWIDE SYSTEM CONTROL 3.42
Control Concepts 3.43
Centralized Control Systems 3.43
Decentralized, Multilevel Control System 3.44
Multijurisdictional Control Systems 3.45

3.11 INCREMENTAL BENEFITS OF DIFFERENT LEVELS OF CONTROL 3.45
Estimating Fuel Consumption 3.45
Estimating Vehicle Emissions 3.46

Section *Page*

Estimating Highway User Costs 3.47
Impacts of Traffic Signal System Improvement 3.47
Project Level Impacts 3.47
Areawide Impacts 3.47
Costs of Traffic Signal System Improvement 3.49
Cost-Effectiveness Comparisons 3.49

3.12 SPECIAL CONTROLS 3.51
Diamond Interchange Control 3.51
Basic Phasing Schemes 3.51
Control Modes 3.53
Urban Interchange 3.56
PASSER-III Model 3.57
Directional Controls 3.59
Priority Systems 3.60
High-Occupancy Vehicle Priority 3.60
Preemption Systems 3.61
Television Surveillance 3.62

3.13 MEASURES OF EFFECTIVENESS 3.62
Total Travel Time 3.62
Total Travel 3.64
Number and Percentage of Stops 3.64
Delay 3.65
Total Minute-Miles of Congestion 3.66

REFERENCES 3.67

TRAFFIC
CONTROL
SYSTEMS
HANDBOOK

3. CONTROL CONCEPTS — URBAN STREETS

3.1 INTRODUCTION

The purpose of this chapter is to present a discussion of urban street traffic control concepts, standard practices, and operational experiences. Special consideration is given to the development of signal timing plans using both manual and computer-aided techniques. To the extent practical, examples of the application of various procedures are provided.

In approaching the planning and design of a traffic signal control system, one must first develop a basic understanding of the concepts of operation that can be applied to control the movement of traffic on urban streets. These concepts can be broadly classified as signalized intersection control concepts and signal-related special control concepts.

Signalized intersection control concepts may be grouped into the following fundamental categories:

- Isolated intersection control — A form of signal control for a signalized intersection through which the flow of traffic is controlled without giving any consideration to the operation of adjacent signalized intersections.
- Arterial intersection control (open network) — A form of signal control for signalized intersections along an arterial street in which major consideration is given to the provision of progressive traffic flow along the arterial. In this case (as opposed to the isolated intersection), consideration must be given to operating the signals as a system.
- Closed network control — A form of signal control for a group of adjacent signalized intersections in which coordination must be considered. A typical example is the control of signals in the central business district (CBD) of a city.
- Areawide system control — A form of traffic signal system control which treats all of the traffic signals in a city (or metropolitan area) or major portion thereof as a total system. The individual signals within this area may be controlled by isolated, open-network, or closed-network concepts.

In addition, signal-related special control concepts can be subcategorized as follows:

- Priority systems — Traffic control strategies which seek to assign priority for the movement of certain types of vehicles such as buses, high-occupancy vehicles (HOV), and emergency vehicles.
- Directional controls — Special controls designed to permit unbalanced lane flow on surface streets.
- Diamond interchange control — Control strategies designed to improve the operational efficiency of freeway diamond interchanges.

3.2 CONTROL VARIABLES

Control variables are measurements, or estimates, of certain variables which describe traffic conditions. They are used as a basis for selecting and evaluating traffic-responsive control strategies. Control variables commonly used for freeway and urban street control include the following:

- Vehicle presence
- Flow rate (volume)
- Occupancy and density
- Speed
- Headway
- Queue length

Generally these traffic variables are sensed by means of presence detectors (refer to Chapter 5). The fundamental methods by which these control variables are measured, or estimated, from presence detector data are described briefly in the following sections.

In addition, certain environmental factors are sometimes also used as control variables to account for the influences of environmental conditions on traffic performance. The environmental conditions include:

- Pavement surface conditions (wet or icy)
- Weather conditions (rain, snow, or fog)

Such conditions are detected by means of environmental sensors (refer to Chapter 5).

25

Vehicle Presence

The presence, or absence, of a vehicle at a given point on a roadway is referred to as presence. A detector closes an electrical circuit when a vehicle enters its field of detection. The circuit is held closed as long as the vehicle remains within the field, up to some maximum time (e.g., 5 min).

Flow Rate

Flow rate is defined as the number of vehicles passing a point on a roadway during a specified period of time. The output of a detector is scanned periodically (e.g., once every 0.1 sec) by the computer, or, the detector output is input to a counter which is read less frequently (e.g., every 4 to 5 sec) by the computer. The volume, Q, of vehicles per hour passing over a detector, is determined by the following equation:

$$Q = N/T \qquad (3.1)$$

Where:

N = Number of vehicles counted by the detector during the time period T
T = Specified time period, in hr

Occupancy and Density

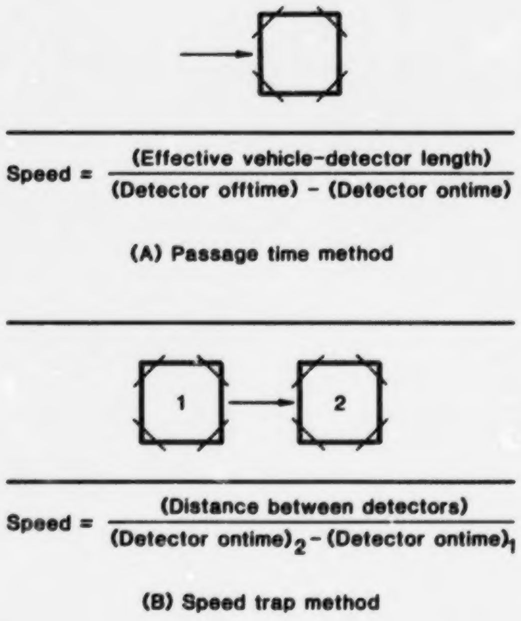
Occupancy can be defined as the percent of time that a given point on a roadway is occupied by a vehicle. Occupancy, θ, is determined by:

$$\theta = \frac{100}{T} \sum_{i=1}^{N} t_i \qquad (3.2)$$

Where:

N = Number of vehicles detected during time period T
T = Specified time period
t_i = Measured presence time of the ith vehicle

Occupancy is frequently used to estimate density, which is the number of vehicles per unit length (usually per lane mile) of roadway. Density, K, per lane mile is derived as follows:



$$\text{Speed} = \frac{\text{(Effective vehicle-detector length)}}{\text{(Detector offtime)} - \text{(Detector ontime)}}$$

(A) Passage time method

$$\text{Speed} = \frac{\text{(Distance between detectors)}}{\text{(Detector ontime)}_2 - \text{(Detector ontime)}_1}$$

(B) Speed trap method

Figure 3.1. Speed measurements using presence detectors

$$K = \frac{5{,}280\,\theta}{100d} \qquad (3.3)$$

Where:

θ = Occupancy (percent)
d = Mean vehicle length, in ft

It should be noted that occupancy is a time-average quantity at a point, whereas density is a spatial average quantity, at a given time. The conditions under which one can apply Equation 3.3 are discussed by Kurkjian (*1*) and Mikhalkin (*2*).

Density is also calculated from volume and space-mean speed measurements where density is equal to volume divided by speed. The expression is vehicles per hour divided by miles per hour equals vehicles per mile.

Speed

The distance traveled by a vehicle per unit time, usually expressed in miles per hour, is termed speed. Either one or two detectors may be used to measure speed (see Figure 3.1). Speed, V, in mph, is determined by:

$$V = \frac{3,600,000d}{5,280\,(t_1 - t_0)} \qquad (3.4)$$

Where:

For the 1-detector, or passage-time, method:

d = Mean vehicle length, in ft
t_0 = Time when the detector turns on, in milliseconds
t_1 = Time when the detector turns off, in milliseconds

For the 2-detector, or speed-trap, method:

d = Distance between detectors, in ft
t_0 = Time when the first detector turns on, in milliseconds
t_0 = Time when the second detector turns on, in milliseconds

Equation 3.4 is accurate for a nonaccelerating vehicle. But, for an accelerating vehicle, a more accurate speed, V, in mph, can be obtained using two detectors and the following equation:

$$V = \left(\frac{1}{2}\right)\frac{d}{t_1 - t_0} + \frac{d}{t_3 - t_2}\left(\frac{3,600,000}{5,280}\right) \qquad (3.5)$$

Where:

d = Distance between detectors, in ft
t_0 = Time when the first detector turns on, in milliseconds
t_1 = Time when the second detector turns on, in milliseconds
t_2 = Time when the first detector turns off, in milliseconds
t_3 = Time when the second detector turns off, in milliseconds

When only one detector is used, a mean vehicle length must be assumed. Since the actual vehicle length varies considerably (e.g., because of an appreciable number of trucks and buses), the use of two detectors is preferable. However, speed traps at representative locations can be used periodically to update the average effective vehicle-detector length to be used for determining vehicle speeds by the passage-time method at single-detector locations. The effective vehicle-detector length, d, in ft, is determined from a speed-trap measurement as follows:

$$d = \left(\frac{1}{2}\right)\left[(t_1^1 - t_0^1) + (t_1^2 - t_0^2)\right]\left(\frac{5,280V}{3,600,000}\right) \qquad (3.6)$$

Where:

V = Speed determined from the speed-trap calculation, in mph
t_{0i} = Time when ith detector of speed-trap turns on, in milliseconds
t_{1i} = Time when ith detector of speed-trap turns off, in milliseconds

Under space-time homogeneity conditions, Wardrop (*3*) was the first to show that speeds of successive vehicles crossing a point should be harmonically averaged to yield the space-mean speed on the roadway section. Similar studies by Breiman (*4*) and Gershwin (*5*) showed that the space-mean speed can be computed from the following equation:

$$\overline{U}_s = N \div \sum_{i=1}^{N} V_i \qquad (3.7)$$

Where:

$\overline{U}_s$ = Space-mean speed over a roadway section, in mph
V_i = Speed of vehicle i crossing a detector station anywhere within the roadway section
N = Number of vehicles detected

Thus, the space-mean speed, $\overline{U}_s$, in mph, for all vehicles detected during a given time period is determined by:

$$\overline{U}_S = \frac{3,600,000}{5,280}\,\frac{d}{N}\sum_{i=1}^{N}\frac{1}{t_i} \qquad (3.8)$$

Where:

N = Number of vehicles detected
t_i = Time interval (ti - t0) measured for the ith vehicle detected, in milliseconds
d = Distance between detectors, in ft
t_0 = Time when the first detector turns on, in milliseconds
t_1 = Time when the second detector turns on, in milliseconds

27

An estimate of the average speed of the vehicles on a section of roadway may be made using the fundamental volume-speed-density relationship for uniform flow:

$$Q = K\,\overline{U}_S \qquad (3.9)$$

Where:

Q = Volume of traffic flow, in vph
K = Density of traffic flow, in vpm
$\overline{U}_s$ = Space-mean speed, in mph

Substituting into Equation 3.9 the expressions for volume and density in Equation 3.1 and 3.3, respectively, and solving for speed, the following equation for average speed, $\overline{U}_s$, is obtained:

$$\overline{U}_S = \frac{100\,dN}{5{,}280\,\theta\,T} \qquad (3.10)$$

Where:

N = Number of vehicles counted by the detector during the time period T (see Equation 3.1)
T = Specified time period, in hr
d = Mean vehicle length, in ft (see Equation 3.3)
θ = Occupancy, in percent

Headway

The time spacing between the front of successive vehicles, usually in one lane of a roadway, is referred to as headway. Headway is measured by a detector as the time difference between the beginning of successive vehicle detections, as shown in Figure 3.2.

Queue Length

The number of vehicles stopped in a lane behind the stop line at a traffic signal is defined as queue length. This variable cannot, however, be measured directly by a single presence detector, although estimates of the queue length are often made from detector data.

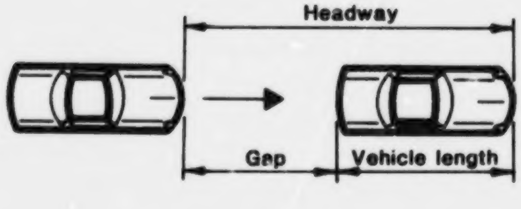


Figure 3.2. Headway determination

For example, if a detector were located upstream some distance from the stop line at a traffic signal, as each vehicle approaching the traffic signal crossed the detector, it would be determined whether or not the vehicle would have to stop. This prediction would be based on the measured speed of the vehicle, signal timing, distance of the detector from the stopline, and the current queue length. If it were predicted that the vehicle would have to stop, one would be added to the current queue length. If the signal were green, the queue length would be reduced in accordance with a predetermined flow rate.

In some cases, two or three detectors would be used to estimate the queue length on an approach. For example, detectors might be installed at three locations on an approach at different distances from the stop line (e.g., 150, 300, and 500 ft). The queue length, Q, would then be estimated on the basis of detector occupancy measurements as being one of the following:

$$Q < 150 \text{ ft}$$

$$150 \text{ ft} \le Q < 300 \text{ ft}$$

$$300 \text{ ft} \le Q < 500 \text{ ft}$$

$$Q \ge 500 \text{ ft}$$

3.3 SAMPLING

The status of vehicle detectors (in terms of vehicle presence) is sampled periodically by the computer. This results in an error in occupancy and speed computations that is directly related to the sampling rate. In general, though the sampling error can be decreased by increasing the sampling rate, it cannot be eliminated.

The relationship between percent error in occupancy and sampling rate is as follows:

$$\%\,E_\theta = 100\,\frac{S}{T + S} \qquad (3.11)$$

Where:

% Eθ = Percent error in occupancy
S = Inverse of the sampling rate, sec per sample
T = Presence time for a vehicle with an average length at a given speed

3.4 FILTERING AND SMOOTHING

Traffic data derived from electronic surveillance are characterized by various degrees of variability about some mean values. The different sources of this variability include the stochastic nature of the variables themselves and the presence of measurement errors. If raw volume data were to be displayed on a CRT or a line printer, an operator would not be able to tell whether "things" are going better or worse. In addition, some real-time control techniques require predictions of what would be the values of traffic variables during the next control period. In such situations, it is necessary to use a smoothing or filtering model in order to extract the average trends in traffic data or make short-term predictions of the control variables.

A smoothing model (or filter equation, as shown in Figure 3.3) is basically an algorithm which processes the incoming detector data as they are received to produce estimates of the underlying system state variables. Since the late 1960s, many research efforts have been made to develop procedures for estimating traffic variables from vehicle detector data. Typical density estimation schemes, mean speed estimation with detector loops, and prediction algorithms for computer-supervised traffic control systems have been described by various previous investigations.

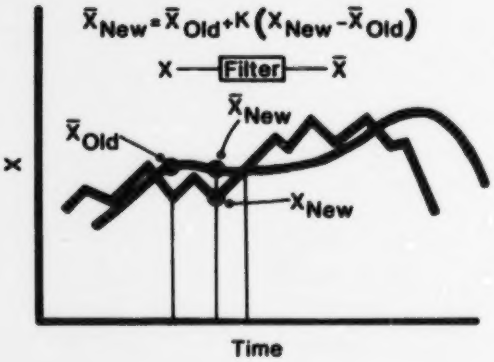


Figure 3.3 Filtering equation

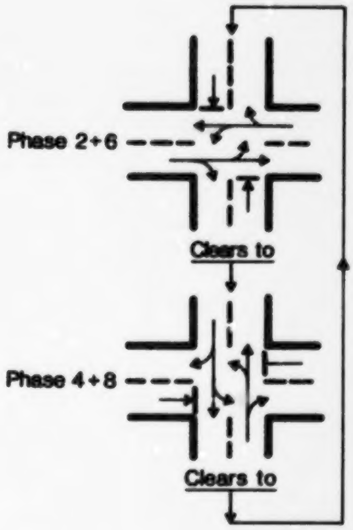


Figure 3.4. Single-ring 2-phase signal sequence

3.5 TRAFFIC SIGNAL TIMING PARAMETERS

The discussion of signalized intersection control concepts and the related signal timing plans requires definitions of some basic terms. These definitions are provided below for convenient reference.

- Cycle length — The time required for one complete sequence of signal intervals (phases)
- Phase — The portion of a signal cycle allocated to any single combination of one or more traffic movements simultaneously receiving the right-of-way during one or more intervals
- Interval — A discrete portion of the signal cycle during which the signal indications (pedestrian or vehicle) remain unchanged
- Split — The percentage of a cycle length allocated to each of the various phases in a signal cycle
- Offset — The time difference (in seconds or in percent of the cycle length) between the start of the green indication at one intersection as related to the system time reference point

3.6 TRAFFIC SIGNAL PHASING

Phasing is a technique to reduce conflicts between traffic movements at signalized intersections. A traffic movement could be either a single vehicular movement, a single pedestrian movement, or a combination of vehicular and pedestrian movements. Precise nomenclature for defining the various signal phases has been adopted and published by the National Electrical Manufacturers Association (NEMA) to eliminate misunderstanding between manufacturers and purchasers. The assignment of right-of-way to traffic movements by NEMA phase numbering standards and the common graphical techniques for representing phase movements are illustrated in Figure 3.4. In this figure, the signal cycle consists of two primary phase combinations (Phases 2 + 6 and Phases 4 + 8) which provide for partial conflict elimination. Major crossing movements are separated, but left-turning movements are allowed to conflict. This may be acceptable if the left-turn movements are light. But if the left-turn movements are heavy, then these movements may require separation also. A 4-phase sequence where all vehicular conflicts are separated is illustrated in Figure 3.5.

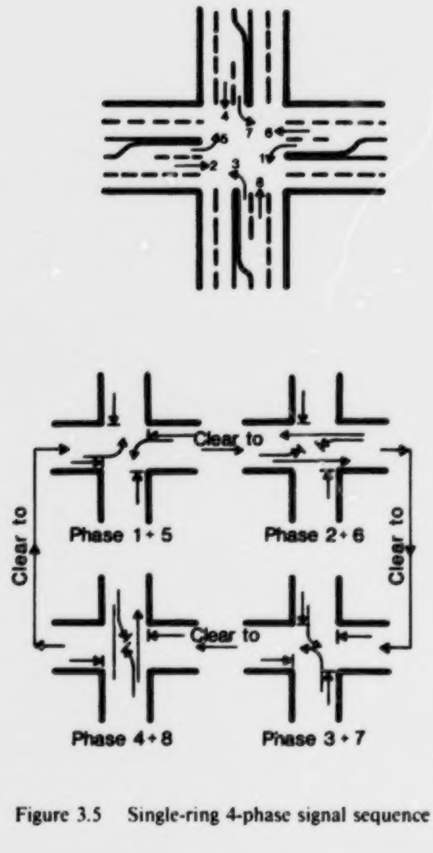


Figure 3.5 Single-ring 4-phase signal sequence

Phasing Options

As suggested by the discussion above, the phasing issue is primarily a left-turn issue. As left-turning volumes and opposing through volumes increase, a left-turn phasing may be considered. Figure 3.6 illustrates a number of possible left-turn phasing options. When the protected left-turn precedes the accompanying through movement, it is called leading left. When the left-turn phasing follows the through movement, it is called lagging left. The most common practice is to allow opposing left-turns to move simultaneously as concurrently timed left-turn phases.

From an operations point of view, the number of phases should be held to a minimum. As the number of phases increases, cycle lengths and delays will generally increase in order to assure that sufficient green time is still available to the other phases. The goals of improving safety (by adding left-turn phases) and improving operations at at a signalized intersection may conflict, particularly with pretimed control. Another left-turn phasing option, that of providing protected/permissive left-turn movement, may be utilized to reduce delay and queueing problems. High speeds, blind or multilane approaches, and other unusual circumstances may prohibit the use of this phasing technique.

Although the *Manual on Uniform Traffic Control Devices* (MUTCD) (*6*) does not provide warrants for left-turn phasing, several states and local agencies have developed their own guidelines for utilizing left-turn phasing. Several representative examples of these guidelines are summarized in the *Manual of Traffic Signal Design* (*7*) and the *Traffic Control Devices Handbook* (*8*).

Variable-Sequence Phasing (Skip Phasing)

The achievement of operational efficiency at a signalized intersection, whether operated in an isolated or coordinated mode, depends largely on the signal phasing versatility of the controller unit being utilized. Variable-sequence phasing or skip-phase capability is particularly important to multiphase intersections where considerable efficiency may be lost due to the number of change intervals and startup delay associated with each phase.

Skip-phase capability can also be provided in modern pretimed controller units. Each set of stored timing plans has a distinct phase sequence that can be changed by time clock, time-base coordinator, or externally, by a remote system master.

Full-actuated traffic control provides an example of variable-sequence phasing. In the intersection shown in the upper part of Figure 3.7, detectors have been located in

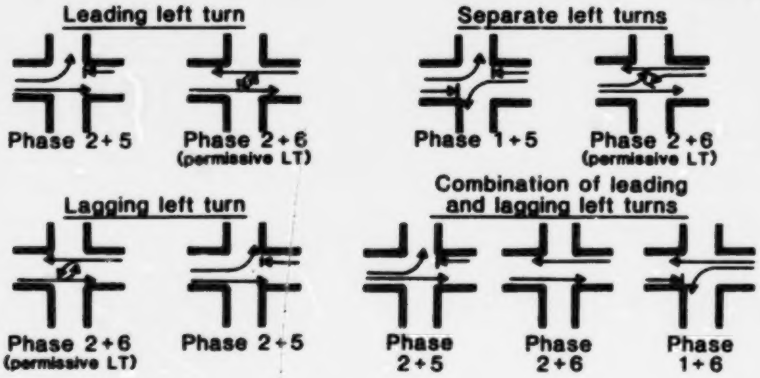


Figure 3.6. Dual-ring left-turn phasing options

all approach lanes. Through the use of detectors and traffic-responsive equipment, it is possible to skip phases when no traffic is present, and to terminate certain movements as soon as the traffic on that movement has been moved into the intersection. This capability then produces a variation in the phasing sequence. Primary phasing options for a full-actuated intersection are illustrated in the lower part of Figure 3.7.

3.7 ISOLATED INTERSECTIONS

Traffic signal control concepts for isolated intersections fall into two basic categories: (1) *pretimed signal control* and (2) *traffic-actuated signal control.* Each type of control offers varying performance and cost characteristics depending on the nature of the installation and the prevailing traffic conditions. Because of the relative complexity of the problem and the rapid changes in the state of the art, there has been no universal "best" method for determining the optimal type of control for a given intersection. General guidelines which can aid the engineer in selecting the appropriate type of signal control have been recently published in the NCHRP Report 233 (*9*) and in the *Manual of Traffic Signal Design* (*7*). However, a prime factor which must always be considered in the selection process is adequacy.

Pretimed Control

Pretimed control assigns the right-of-way at an intersection according to a predetermined schedule. The sequence of right-of-way assignments (phases), and the length of the time interval for each signal indication in the cycle is fixed, based on historic traffic patterns. No recognition is given to the current traffic demand on the intersection approaches unless detectors are used. The major elements of pretimed control are (1) fixed cycle length, (2) fixed phase lengths, and (3) number and sequence of phases.

This type of control is well suited to intersections with predictable traffic patterns, or frequent occurrence of saturated conditions. A pretimed controller can be an electromechanical device (using motors, gears, and relays), or it can be a solid-state or microprocessor-based device. A discussion of these types of controllers is presented in Chapter 6.

Traffic-Actuated Control

Traffic-actuated control of isolated intersections attempts to adjust green times continuously, and, in some cases, the sequence of phasing (through skipping of phases with no traffic demand). These adjustments occur in accordance with real-time measures of traffic demand obtained from vehicle detectors placed on one or more of the approaches to the intersection. The full range of actuated control capabilities depends on the type of equipment employed and the operational requirements.

In addition to the yellow change and red clearance intervals, the basic timing parameters in a traffic-actuated phase are:

- Minimum green
- Passage time interval (vehicle interval)
- Maximum interval

A typical intersection approach with a vehicle detector is illustrated in Figure 3.8. The distance from the detector to the stop line influences the time setting of the minimum green interval, the passage time interval, and the

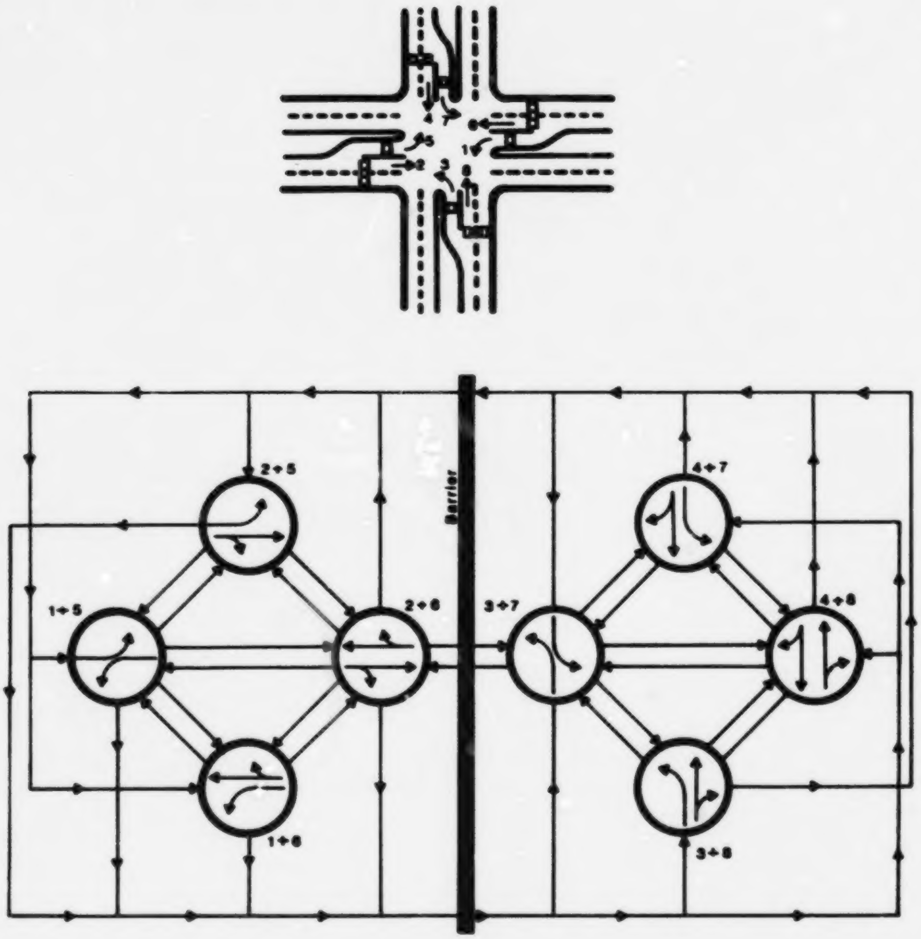
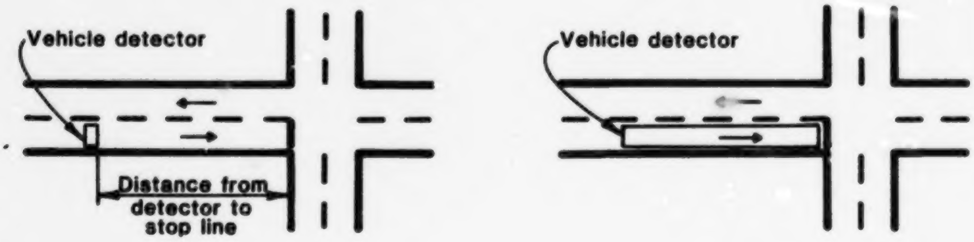


Figure 3.7. Primary phasing options for 8-phase dual-ring control (left turns first)

maximum interval. It is important to emphasize the importance of on-site fine tuning of all controller unit interval settings to ensure appropriateness and verify operations.

Minimum Green Interval. In basic traffic-actuated control (the signal controller does not have a volume-density feature), the minimum green interval depends on the number of cars that can potentially be stored between the detector and the stop line. Once this number of vehicles is known, the minimum green interval can be calculated, and it remains constant. When point detection is used, the minimum green interval times for various detector setback distances are computed assuming a startup delay of 4 sec, an average headway between discharging vehicles of 2 sec, and that the minimum green time must be at least (4 + 2 n) where n is the number of vehicles between the detector and the stopline. The value of n is usually computed assuming an average vehicle length of 20 ft. For detectors located in excess of approximately 120 ft from the stop line, the minimum green time may be equal to 18 sec or longer. The length of minimum green time reduces the operational efficiency of the control in terms of inability to respond to changes in traffic demand. Therefore, 120 ft is often selected as an upper limit for detector placement.


Vehicle detector
Distance from detector to stop line
Vehicle detector

(A) Point detection

(B) Long-loop presence detection

Figure 3.8. Traffic detection on intersection approach

With long loop presence detection (or a series of short loops), the initial interval is set close to zero when the detector loop ends at the stop line. If the loop ends at some distance from the stop line, this distance is used to determine the initial interval as in the case of point detection.

In traffic-actuated control (the signal controller has a volume-density feature), the length of the initial interval changes based on the number of vehicle actuations stored for a phase while other phases are being serviced.

When there are serviceable calls on opposing phases, and no additional vehicles cross the detector, then the phase will be terminated at the end of this minimum green time. However, where pedestrian crossing needs to be considered and there are no separate pedestrian crossing indications (e.g., WALK-DONT WALK), the minimum green time should ensure adequate pedestrian crossing time.

Passage Time Interval. This vehicle interval (sometimes referred to as an extension interval or unit extension) is the time required by a vehicle to travel from the detector to the intersection. It also represents the maximum time gap between vehicle actuations that can occur without losing the green indication with a call waiting on an opposing phase. As long as the time between vehicle actuations is shorter than the vehicle interval (or a preset minimum gap which will be discussed later), the green will be retained on that phase subject to the maximum interval. To assure "snappy operation," the vehicle interval should be set as short as practical.

Once the passage time interval timing is initiated and an additional vehicle is detected, then the present vehicle interval timing is cancelled and a new vehicle interval timing is initiated. This process is repeated for each additional vehicle detection until (1) a gap-out occurs (the gap between detections is greater than the vehicle interval or a preset minimum gap), or (2) a max-out occurs (the interval timing reaches a preset maximum and a pedestrian or a vehicle call has been placed for another phase). In either of these two cases, the timing of a yellow change interval is initiated and the phase is terminated. If the vehicle interval is not completely timed out (because of the maximum override), then a recall situation is set and the timing will return to this phase at the first opportunity. Figure 3.9 illustrates the situation where successive actuations occurred, all gaps were shorter than the passage time interval, and the preset maximum green interval was reached.

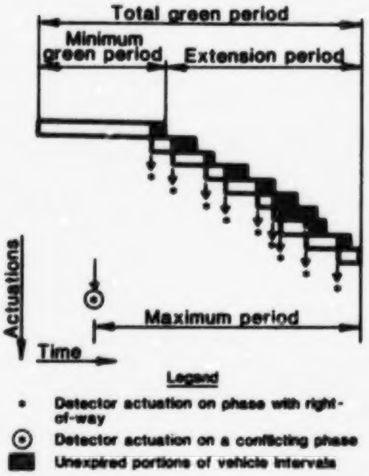

Total green period
Minimum green period
Extension period
Actuations
Time
Maximum period
Legend
• Detector actuation on phase with right-of-way
⊙ Detector actuation on a conflicting phase
■ Unexpired portions of vehicle intervals

Figure 3.9. Schematic of actuated phase interval

Source: Reference (7)

33

With long loop presence detection, the passage time interval is set close to zero since the signal controller continuously extends the green as long as the loop is occupied. In this case, the critical time gap is the time required for a vehicle to travel a distance equal to the loop length plus the vehicle length. If a series of short loops are used, they are treated as a long loop provided that the distance between the loops is less than the vehicle length; otherwise a short vehicle interval can be used to produce the equivalent effect of a single long loop.

Maximum Green Interval. This time setting determines the maximum length of time that a phase can hold the green in the presence of a conflicting call. It may be expressed in terms of total green time or in terms of vehicle extension limit. The normal range for the length of maximum green interval is between 30 and 60 sec.

The following are the principal operational modes associated with traffic-actuated control. These are discussed further in Chapter 6:

- Semiactuated mode
- Full-actuated mode
- Volume-density mode
- Queue-length mode
- Lane-occupancy mode

Basic Considerations

In the operation of an isolated intersection, the following three basic items must receive major consideration relative to the signal control concepts that are utilized:

- Safe and orderly traffic movement
- Vehicle delay
- Intersection capacity

Vehicle delay results from stopped time delay (time waiting against red signal) and total delay (stopped time delay plus delay because of deceleration for stop and startup delay). Ideally, it is desirable to minimize total delay, to maximize intersection capacity, and to reduce the potential for accident-producing conflicts. Unfortunately, these desirable attributes are not always compatible. For example, delay may be minimized by using as few phases as possible and the shortest practical cycle length. To reduce accidents, multiple phases and longer cycles may be considered, as well as strategic placement of approach detectors to eliminate effects of a possible dilemma zone. Therefore, it is necessary to exercise engineering judgment to achieve the best possible compromise among these objectives.

Traffic Flow

In working with intersection delay or capacity, a fundamental consideration is the flow characteristics of traffic. Vehicles occupy space, and some space must be provided between vehicles for a safety margin. With vehicles moving along continuously in a single lane (such as a freeway lane), the number of vehicles passing a given point over time will be a function of the average time headway between vehicles. For example, if the average time headway is 2 sec, then a volume of 1,800 vph (3,600 sec/hr x 1 veh/2 sec) results.

Traffic flow capacity at a signalized intersection is influenced by two factors. First, conflicting flows occur where two vehicles attempt to occupy the same space at the same time. This conflict requires the allocation of the right-of-way to one line of vehicles while the other line of vehicles must wait. The interruption of flow for the assignment of right-of-way introduces the second complicating factor of vehicle delay. Vehicles are delayed as they slow down to stop, and also a starting delay is experienced when they are again permitted to proceed. These factors (interruption of flow, stopping, and starting delay) reduce capacity and increase delay at a signalized intersection as compared to free-flow operations on a street or freeway. Vehicles which arrive during a red interval must stop and wait for a green indication. When the green indication is received, they start and proceed through the intersection. Figure 3.10 provides a graphical illustration of this flow. The delay which occurs as the vehicles start moving is followed by a period of relatively constant flow. In terminating the traffic flow, some time is also lost at the end of a green interval.

Data on typical vehicle headways (time spacing) at a signalized intersection as reported by Greenshields (*10*) are presented in Table 3.1. These data are useful in illustrating basic concepts of intersection delay and capacity.

Intersection Timing Requirements

As a basic requirement for isolated intersection control with pretimed equipment, it is necessary to determine the cycle length, the phase lengths (or cycle split), and the number and sequence of phases. This timing must, of course, be related to the characteristics of traffic flow at the intersection. If pretimed equipment is to be utilized, then desired values must be established for each phase length (green interval plus yellow change interval) and for the total cycle length.

If traffic-actuated control equipment is to be utilized, then the cycle length and phase lengths will be automatically determined by the control equipment based upon

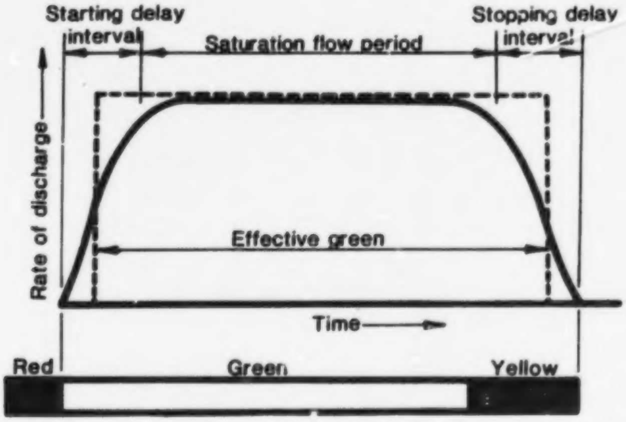


Figure 3.10. Queue discharge across the stop line

Table 3.1. Vehicle headway data

Position in Line	Observed Time Spacing (Sec)	Time Spacing at Constant Flow (Sec)	Added Startup Time (Sec)	
1	3.8	2.1	1.7	
2	3.1	2.1	1.0	
3	2.7	2.1	0.6	Total
4	2.4	2.1	0.3	3.7
5	2.2	2.1	0.1	
6 and over	2.1	2.1	0.0	

Source: Reference (*10*)

the detection of traffic characteristics on the various approaches. The major requirement is to set the proper timing values for each of the functions provided by the controller unit.

Intersection Timing — Webster

Webster (*11*) utilized computer simulation and extensive field observations to provide an excellent study of isolated intersection operation. This work is applicable to either regular unchannelized or high-type fully channelized intersections. In considering the vital element of vehicle delay, Webster developed the classic equation shown as follows:

$$d = \frac{C\,(1-\lambda)^2}{2\,(1-\lambda X)} + \frac{X^2}{2q\,(1-X)} - 0.65\left(\frac{C}{q^2}\right)^{1/3} X^{(2+5\lambda)} \qquad (3.12)$$

Where:

d = Average delay per vehicle on the intersection approach under consideration
C = Cycle length
λ = Proportion of the cycle which is effectively green for the phase under consideration
q = Flow rate.
S = Saturation rate (1,800 vph)
X = The degree of saturation. This is the ratio of the actual flow to the maximum flow which can be passed through the intersection from this intersection approach and is given by $X = q/S$.

A fundamental assumption of Webster's work is that of random vehicle arrivals and that saturation does not occur.

Optimum Settings. Webster shows that a critical lane can be designated and defined as the one with the highest ratio of flow to saturation flow. This ratio is denoted by the symbol Y, where $Y = \text{Max}\ (q/X)$ for a given phase.

An optimum cycle-length formula was developed by Webster for pretimed application. This formula, yields the cycle length that will produce minimum total vehicle delay. A second formula was developed (*22*) for similar cycle length calculations for actuated applications. These are expressed as follows:

Pretimed:

$$C_o = \frac{1.5\ L + 5}{1 - \sum_{i=1}^{n} Y_i} \qquad (3.13)$$

Actuated:

$$C_o = \frac{1.3\ L}{1 - \sum_{i=1}^{n} Y_i} \qquad (3.14)$$

Where:

C_o = Optimum cycle length, sec
L = nl R
n = Number of phases
l = Average lost time per phase, sec/sec
R = Time during each cycle when all signals display red simultaneously, sec
Y_i = Critical lane flow (ith phase, vph) saturation flow (vph)

The above formula may be utilized to select the cycle length at a given isolated intersection. The equations yield cycle lengths (C_o) that are usually shorter than those that will be defined by other methods for cycle-length determination. This correlates with other work (*12*) which indicates that cycle lengths should be as short as possible. It is common to find, in practice, that cycle lengths longer than necessary are used. Webster also concluded that delay is not significantly increased by cycle-length variation in the range of 0.75 C_o to 1.5 C_o. Webster's methods are sensitive to errors in estimates of vehicle flow rate and saturation flow. See work by Alsop (*13*) for a discussion of this subject.

Webster further recommended that the distribution of the green time to each phase be proportional to the critical lane volumes on each phase. The formula for determining green time for a two-phase pretimed intersection is as follows:

$$G_i\ (\text{net green time}) = C_0 - A_1 - A_2 - nl \qquad (3.15)$$

Where:

C_o = Optimum cycle length, sec
A_1 = Yellow time on Phase 1, sec
A_2 = Yellow time on Phase 2, sec
n = Number of phases
l = Lost time per phase, sec

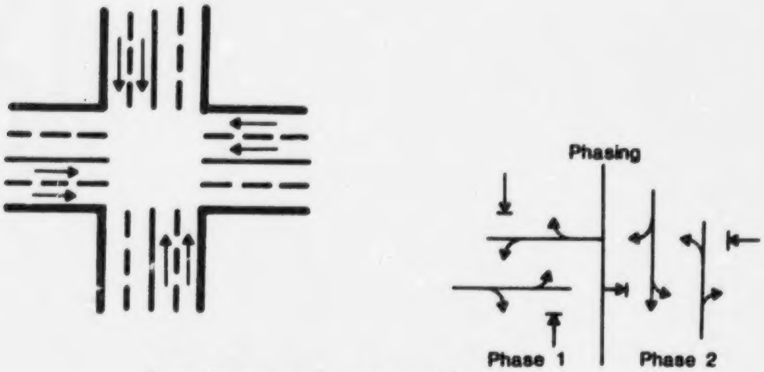
Example. To illustrate the use of Webster's methods consider the intersection shown in Figure 3.11. Assume saturation flow is 1,800 vph, and lost time per phase is 5.2 sec:

$$Y_i = \frac{\text{observed flow}}{\text{saturated flow}}$$

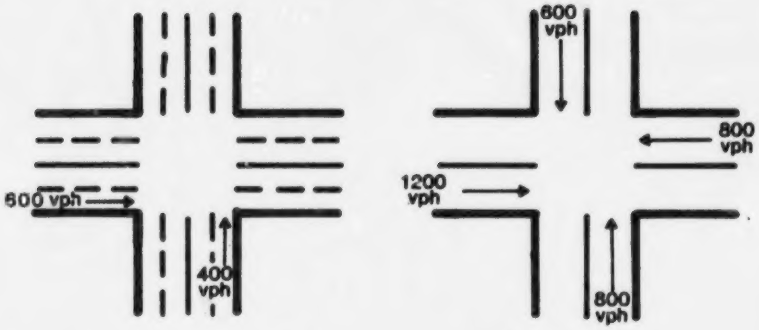
$$Y_1 = \frac{600}{1{,}800} = 0.333$$

$$Y_2 = \frac{400}{1{,}800} = 0.222$$

$$\sum Y_i = 0.333 + 0.222 = 0.555$$


Phasing
Phase 1
Phase 2

Two lanes per approach
(2-way operation)


600 vph
400 vph
600 vph
800 vph
1200 vph
800 vph

Critical lane volumes   Approach volumes

Figure 3.11. Example intersection

$$C_0 = \frac{1.5\,L + 5}{1 - \Sigma Yi}$$

$$C_0 = \frac{1.5\,(2)\,(5.2) + 5}{1 - 0.555} \qquad (3.16)$$

$$C_0 = \frac{15.6 + 5}{0.445} = \frac{20.6}{0.445} = 46.3 \text{ sec.}$$

Use $C_0 = 46$ sec

Assume $A_1 = A_2 = 4$ sec

$G_t = C_0 - A_1 - A_2 - nl$

$G_t = 46 - 4 - 4 - 10.4 = 27.6$

Critical lane volumes = 600 + 400 = 1,000

$$G_1 = \frac{600}{1000}\,(27.6) = 16.7 \text{ sec}$$

$$G_2 = \frac{400}{1000}\,(27.6) = 10.9 \text{ sec}$$

Signal timing would then be as follows:

Phase 1 = G_1 + Yellow + lost time
= 16.7 + 4 + 5.2 = 25.9 sec

Phase 2 = G_2 + Yellow + lost time
= 10.9 + 4 + 5.2 = 20.1 sec

Cycle length = Phase 1 + Phase 2
= 25.9 + 20.1
= 46 sec

Intersection Timing — Critical Movement Analysis

A second approach to intersection capacity analysis and the development of timing plans is presented in this section to broaden the basic understanding of signalized intersection operation. A considerable amount of research on the design and signalization of complex intersections was conducted and reported by the Texas Transportation Institute (*15*). This work produced techniques for evaluating and designing complex intersections. The following material presents some basic concepts derived from this work and similar work presented in January 1980, in TRB publication entitled *Circular 212 — Interim Materials on Highway Capacity* (*16*).

Consider a single lane on one approach to a signalized intersection and let n_p = the number of vehicles that can move into the intersection during one green interval from this lane. Then,

$$n_p = \frac{G - D}{H} + 2 \text{ (veh/cycle)} \qquad (3.17)$$

Where:

G = Length of green interval, sec
D = Time required for first two vehicles to move into intersection, sec
H = Average time-headway for remaining vehicles, sec

This formulation states that, after approximately two vehicles have started and moved into an intersection on a green indication, the remaining vehicles in the approach queue will move with a near constant headway of H. Assuming D = 5.8 sec and H = 2.0 sec, then,

$$n_p = \frac{G - 5.8}{2.0} + 2 = \frac{G - 1.8}{2.0} \qquad (3.18)$$

Equation 3.18 assigns a starting delay of 1.8 sec to get a queue of vehicles moving into a signalized intersection after receiving a green indication.

Multiplying Equation 3.18 by the number of cycles per hour (3.600/c) produces nh the number of veh/hr per lane as follows:

$$n_h = \left(\frac{G - 1.8}{2}\right)\left(\frac{3.600}{C}\right) \qquad (3.19)$$

Where:

C = Cycle length, sec

If an intersection with four phases such as that shown previously in Figure 3.5 is considered, then each lane on each phase can produce the vehicle movement given by Equation 3.19 since all conflicting movements are separated by the phasing arrangement.

If the critical lane on each approach is considered (where the critical lane is defined as the lane moving the largest volume of traffic per phase), then a critical-lane capacity (Nc) can be developed for the total intersection as follows:

$$N_c = \sum_{i=1}^{K} N_i \qquad (3.20)$$

Where:

K = Number of phases and
N_i = Critical lane capacity on Phase i

Also, by substitution,

$$N_c = \sum_{i=1}^{K} \left(\frac{G_i - 1.8}{2.0}\right)\left(\frac{3.600}{C}\right) \qquad (3.21)$$

$$\frac{\sum_{1}^{K} G_i - 1.8K}{2.0}\left(\frac{3.600}{C}\right) \qquad (3.22)$$

Cycle length C is equal to total green time plus yellow time, that is

$$C = \sum_{1}^{K} G_i + K\,(A) \qquad (3.23)$$

or

$$\sum_{i}^{K} G_i = C - K\,(A) \tag{3.24}$$

Where:

A = Yellow change interval, sec

Substituting in Equation 3.22,

$$N_c = \frac{C - 1.8K\,(A)}{2.0}\left(\frac{3{,}600}{C}\right) \tag{3.25}$$

for A=3 sec,

$$N_c = 1{,}800 - K\left(\frac{8{,}640}{C}\right) \tag{3.26}$$

Equation 3.26 thus expresses the critical capacity (sum of the capacity for all critical lanes) of a signalized intersection. It indicates that (assuming D = 5.8 sec, H = 2.0 sec) the critical capacity is 1,800 veh/hr less the lost capacity due to the assignment of the right-of-way to the various phases of the intersection (yellow time and starting delay per phase).

Equation 3.26 is very useful in understanding the impact of cycle length and number of phases on intersection capacity. Table 3.2 provides values for N_c for various cycle lengths with both 2-phase and 4-phase operation. It also illustrates the percent increase in N_c for each 10-sec cycle length increase. A plot of the values in Table 3.2 is shown in Figure 3.12. The following observations seem pertinent:

- Expanding the cycle length for a 4-phase signal is much more beneficial than for a 2-phase signal.
- The increase in capacity obtained by increasing cycle length begins to become marginal for cycle lengths in excess of 60 sec on 2-phase signals and for cycle lengths in excess of 80 sec for 4-phase signals.
- Capacity is significantly reduced by increasing the number of phases from 2 to 4.

The third observation that capacity is significantly reduced by increasing the number of phases from two to four should not be interpreted to mean that one should never use 3-phase or 4-phase signalization. Multiphase (three or more phases) operation is often necessary and very beneficial in reducing vehicle conflicts. However, multiphase operation should only be used when warranted and careful attention should be given to the development of a good timing plan (cycle length and split).

Intersection Timing — Traffic-Actuated Control

The use of traffic-actuated control equipment at isolated signalized intersections implies that the timing plan will be continuously adjusted and will be responsive to traffic demand registered at the intersection. One might expect that delay will thus be minimized and the maximum capacity of the intersection will be obtained. This may not be the case, however, unless careful attention is given to the type of equipment installed, the mode of operation, the location of detectors, and the timing settings that are established. The reader is referred to Chapters 5 and 6 of this Handbook for a discussion of types of detectors and controllers and proper design and operation.

A good and easy check on the performance of a traffic-actuated controller is to observe cycle lengths and the number of cars moved for a given amount of green time during periods of peak flow. If the cycle lengths are excessive (100 sec or greater) and if inefficient use of the green time is observed, then traffic performance at the intersection can probably be improved. This improvement might require revised design, timing changes, or equipment repair.

Intersection Timing — Other Considerations

The intersection timing techniques previously discussed are, of course, not the only methods available for developing timing plans. Basic research on traffic operation at signalized intersections has been conducted by Greenshields (*10*). *The Highway Capacity Manual* (*17*) should be consulted for a comprehensive treatment of intersection capacity. The *Transportation and Traffic Engineering Handbook* (*18*), the *Manual on Uniform Traffic Control Devices* (*6*), the *Manual of Traffic Signal Design* (*7*), and a textbook by Pignataro (*19*) are also recommended as references on this subject.

In addition to cycle length and split calculations, there are several other important considerations in developing timing plans for pretimed signal control. Some of these considerations are also applicable to traffic-actuated signal timing.

The provision for pedestrian movement at an intersection is a functional consideration and may often be a controlling factor in establishing a given timing plan. Another important consideration in signal timing is that of establishing the length of the phase-change period.

Table 3.2. Capacity values

Cycle Length (Sec)	Two-Phase Operation		Four-Phase Operation	
	N_c	Percent Increase	N_c	Percent Increase
40	1318.0	-	936.0	-
50	1454.4	10.3	1108.8	18.5
60	1512.0	4.0	1224.0	10.4
70	1553.1	2.7	1306.3	6.7
80	1584.0	1.9	1368.0	4.7
90	1608.0	1.5	1416.0	3.5
100	1627.2	1.1	1454.4	2.7
110	1642.9	0.9	1485.8	2.1
120	1656.0	0.8	1512.0	1.7
130	1667.1	0.7	1534.2	1.5
140	1676.6	0.6	1553.1	1.2
150	1684.8	0.5	1569.6	1.1

Source: Reference (9)

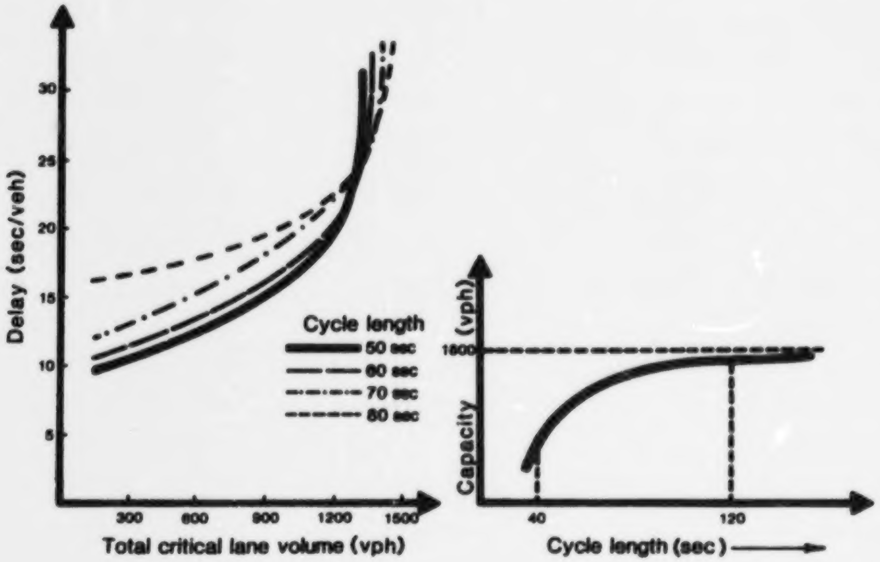


Figure 3.12. Cycle length relationship to capacity and delay

This period may consist of only a yellow change interval or may include an additional red clearance interval. The purpose of the yellow interval is to warn traffic of an impending change in the right-of-way assignment. For a detailed discussion of these elements the reader is referred to the *Traffic Control Devices Handbook* (8).

In considering control concepts and strategies for isolated signalized intersections, it is also necessary to be aware of traffic flow fluctuations and the random nature of vehicle arrivals at isolated intersections. Traffic flow is, of course, influenced by the patterns of human activity during the day and thus usually exhibits three daily peak periods (a.m., noon, p.m.). Drew (*15*) has shown that even within a peak hour the 5-min flow rates can be as much as 15 to 20 percent higher than the average flow rate for the total peak hour period. He has further shown that the best predictor of vehicle arrivals for isolated intersections is a Poisson distribution, which indicates that a considerable variation in arrival volumes can be expected on a cycle-to-cycle basis. The work of Drew (*15*) presents a comprehensive treatment of the design and signalization of intersections.

Intersection Timing — Available Computer Software

Manual design techniques for intersection signal timing are useful tools, but they are inefficient in conducting comprehensive analysis and evaluation of the alternative timing plans for a given set of geometric and traffic conditions. Since the early 1960s, many efforts have been made to develop computer models which can assist the traffic engineer in developing cost-effective operational improvements at street intersections. A survey of available computer models which can be used for this purpose is provided by Gibson (*20*).

Computer models for intersection signal timing which are well documented include the following:

- SOAP Model (Optimization)
- TEXAS Model (Simulation)

A brief overview of these models is presented in the following material in an effort to acquaint the reader with the basic state of the art in this area.

SOAP-84 Model. The Signal Operations Analysis Package (SOAP) was developed in 1977, with updates in 1982 and 1984, by the State of Florida and the University of Florida Transportation Research Center for the Federal Highway Administration. It is a computer model for developing signal timing plans for isolated intersections. A wide range of control alternatives can be evaluated, including pretimed or multiphase-actuated control. The typical physical condition analyzed by SOAP is a 4-legged intersection with left turns, through traffic, and right turns (*21*).

SOAP determines the optimum signal timing and phasing by three computational functions: design, analysis, and evaluation (*20*). The design function of SOAP examines all legitimate phasing sequences for a given intersection configuration and traffic conditions, and selects the one that can be executed by using the minimum amount of green time. This design is then returned to the user. The next step is controller dial assignment and timing. The user must decide on the number of traffic patterns to be analyzed and can assign them to the appropriate dial. If any pattern is unassigned, SOAP will do so, based on traffic demands. If traffic-actuated control is desired, no traffic pattern assignments are made, and SOAP makes its computations accordingly. Optimum cycle length is then determined by SOAP's optimization logic to minimize total intersection delay subject to constraints on the amount of queuing that can be tolerated. The green is then allocated among conflicting movements based on techniques that are related to the critical movement analysis as described in the Transportation Research Board's Circular 212 (*16*).

In the analysis function of SOAP, several measures of effectiveness are computed including delay, stops, fuel consumption, volume-to-capacity ratio, and left-turn conflicts. This allows the user to quantify the effect of either the designed timing or any other timing scheme. Finally, the evaluation function of SOAP produces comparisons of the different design schemes. Implementation packages for using SOAP-82 on 16/32 bit mainframe and minicomputers with FORTRAN compilers, and on IBM-PC (MS-DOS), Apple (UCSD p-system), and Apple (CPM) microcomputers are available from FHWA (*22*).

TEXAS Model. The SOAP model described earlier is a model that deals primarily with signal timing. The Traffic Experimental and Analytical Simulation (TEXAS) model is a simulation evaluation tool, now written in FORTRAN, that was developed by the Center for Highway Research at the University of Texas at Austin for the Texas Department of Highways and Public Transportation (*23*). The TEXAS model does not recommend design decisions; rather it provides rigorous analysis of the particular set of input conditions. The user can evaluate alternative designs by performing several simulations with varied input parameters or data. The geometry processor, GEOPRO, translates the user input data into the required geometry information. The driver-vehicle processor, DVPRO, randomly generates the individual driver-vehicle units based on a variety of user data and program default values. The particular driver characteristics and the vehicle generation are treated stochastically. The simulation processor, SIMPRO, microscopically processes each driver-vehicle unit through the intersection in a fixed, discrete time increment, and accumulates data on the vehicle performance and traffic interaction.

Although the TEXAS model is a very useful and powerful tool, it has some limitations and requires 512 K bytes of memory. The model does not provide for the interaction between pedestrians and vehicles moving simultaneously. Second, the intersection approaches must be straight and at zero grade. However, the effect of grade can be compensated for indirectly by using different headway distributions or parameters. The TEXAS model will produce estimates of fuel consumption and vehicle exhaust emissions when the Center for Highway Research finishes work on adding these measures of effectiveness to the traffic simulator in 1985 (*21*). Also scheduled are changes in input structure to provide interactive data input and program changes to make it transportable.

3.8 ARTERIAL STREET CONTROL

Arterial street control as defined earlier is concerned with controlling signals along an arterial street so as to give major consideration to the provision of progressive traffic flow along the arterial. In this case (as opposed to isolated intersection operation), consideration must be given to the operation of the signals as a system.

Arterial street signal systems form what will be termed an open network, as compared to a closed network, as illustrated in Figure 3.13. The basic approach to arterial street signal control considers that vehicles traveling along the arterial street are released in platoons from a signal, and hence travel in platoons to the next signal. Thus, it becomes desirable to establish a time relationship between the beginning of the arterial green at one intersection and the beginning of the arterial green at the next intersection so that static queues may receive a green indication on their approach to a signalized intersection in advance of arriving platoons from upstream on the arterial. This permits the continuous flow of traffic along an arterial street and aids in reducing delay.

This traffic flow control concept for arterial streets can be presented graphically by a technique known as a time-space diagram, as shown in Figure 3.14. This figure introduces the need for several definitions which are presented as follows:

- Through-band — The space between a pair of parallel speed lines which delineates a progressive movement on a time-space chart.
- Band speed — The slope of the through-band representing the progressive speed of traffic moving along the arterial.
- Bandwidth — The width of the through-band in seconds indicating the period of time available for traffic to flow within the band.

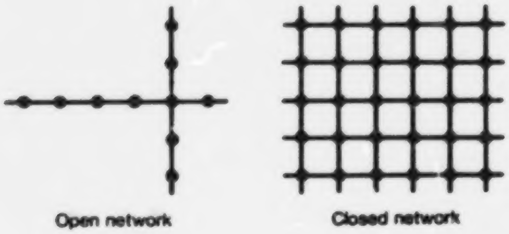


Figure 3.13. Signal networks

The use of 1-way or 2-way operation is a major consideration in developing timing plans for an arterial street. If the street is 1-way, then full use of the through-band for progressive movement can be obtained. If the street is 2-way, the problem of providing progression in both directions is much more difficult. Good 2-way progression is dependent upon signal spacing which, for ideal conditions, must be the same for all intersections and (depending upon the progression speed selected) 800 to 1,000 ft or greater. These conditions rarely exist, and compromises must then be made in the bandwidth and progression speed achieved.

Since the offset relationship must be obtained over time, it is necessary to utilize a common cycle or some multiple of a common cycle throughout the system. The cycle splits may vary at each intersection, but the point of beginning of the major street green must be constant.

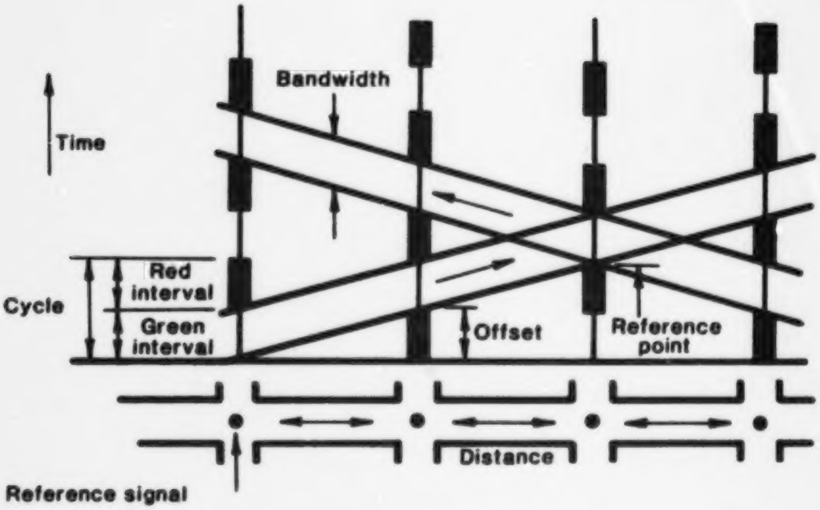
Timing Plan Elements

To establish a control system for an arterial street (or open network), it is necessary to develop a timing plan for all of the signals in the system. Such a timing plan consists of the following elements:

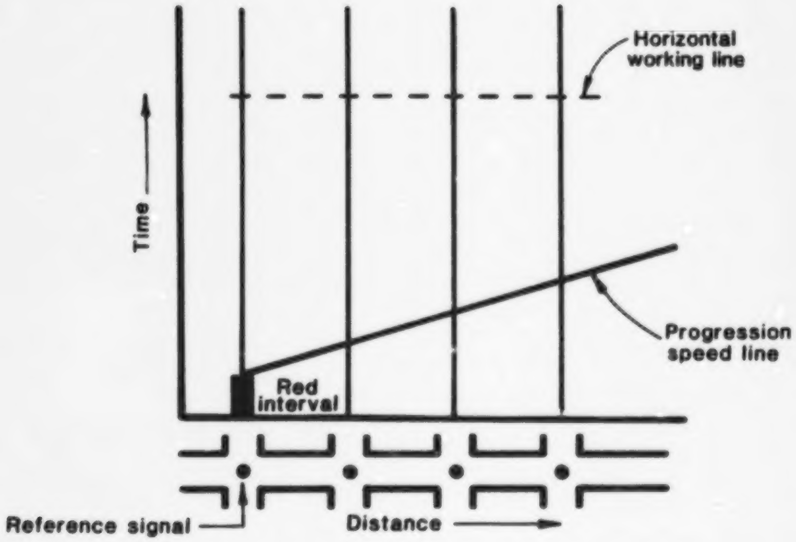
- Cycle length — This *must be the same* (or some multiple) for all signals in the system. Cycle length is usually established by examining traffic flow requirements at each intersection and computing the required length for each intersection.
- Cycle splits — A determination of the length of the various signal phases must be made for each individual intersection in the system. Phase lengths (splits) may vary from intersection to intersection.
- Offset — A determination of an offset value must be made for each intersection in the system. The offset is usually established with reference to one master intersection in the system.

Traffic Flow Variations

In determining timing plans for arterial streets one is faced with the problem of traffic flow variation. A given timing plan is developed for a given set of traffic conditions. When these traffic conditions undergo substantial change, the value of the timing plan is greatly reduced. Two basic types of traffic flow variations can occur as follows:


Time
Bandwidth
Cycle
Red interval
Green interval
Offset
Reference point
Distance
Reference signal

a. Time-space diagram


Time
Horizontal working line
Progression speed line
Red interval
Reference signal
Distance

b. General technique for timing plan development

Figure 3.14. Time-space diagram and graphic technique

- Traffic flow at individual intersections — Traffic volumes can increase or decrease at one or more signal locations in the system. These changes can then alter the cycle-length requirement or the cycle split at the affected intersections.
- Traffic flow direction — The volume of traffic flow

along the arterial can vary directionally on a two-way arterial. Using an inbound-outbound flow designation, three basic conditions can exist as follows:

1. Inbound flow is greater than outbound flow.
2. Inbound flow is approximately the same as outbound flow.
3. Outbound flow is greater than inbound flow.

For the first condition (usually in a.m. peak), one would want a timing plan to favor progressive movement in the inbound direction. For the second condition (off-peak flow), a timing plan which would favor inbound and outbound flow equally would be desirable. For the third condition (usually p.m. peak), a timing plan to favor outbound flow is desired.

Early control techniques usually attempted to provide at least three timing plans (a.m., off-peak, p.m.), which were selected on a time-of-day basis. Traffic-responsive control systems can now automatically adjust timing plans at shorter intervals based upon a measure of traffic flow on the arterial.

Timing Plan Development

In the analysis of procedures for determining timing plans for arterial streets, three basic categories of techniques can be identified as follows:

- Manual techniques — Manual calculations and/or graphical analysis to determine cycle length, splits, or offsets.
- Offline computer techniques — Techniques which utilize computer software models to make necessary calculations to determine the timing plans. The term offline indicates that the timing plans are determined and then implemented without direct interaction with the signal system or traffic flow conditions on the arterial.
- Online computer techniques — Techniques which utilize a computer traffic control system to (1) collect data on traffic flow conditions, (2) make calculations to determine a desired timing plan, and (3) implement or adjust the timing plan in very short time intervals such as each cycle, every 5 min, or every 15 min. Thus, a traffic-responsive system with dynamic or real time timing plan generation is achieved.

The most pertinent techniques within these three categories will be discussed to present basic state-of-the-art technology in this area.

Manual Techniques. In order to develop a timing plan for an arterial signal system, it is first necessary to collect a considerable amount of data about the system. These data would include the following:

- Geometric data
  - ☐ Intersection spacing (stop line to stop line)
  - ☐ Street geometrics (width, lanes, approaches, etc.)
- Traffic flow data
  - ☐ Traffic volumes including turning movement counts
  - ☐ Traffic flow variations
  - ☐ Speed limitations

Once the field data were available, then the following steps could be taken:

1. Prepare a graphical display of the signal system, similar to Figure 3.14.
2. Analyze the traffic flow variations by direction on the arterial, and determine the probable number of timing plans required. This might be as few as three timing plans (a.m., off-peak, p.m.), or transition timing plans (a.m. to off-peak to p.m. or reverse) could be desired, with as many as 6 to 10 timing plans considered.
3. For each of the timing plans to be developed, examine traffic flow conditions at the individual intersections and determine cycle-length and cycle-split requirements. These requirements could be developed utilizing the basic technology discussed in the material on isolated intersections.
4. Conduct a graphical analysis to determine offsets for each of the desired timing plans. The graphical analysis proceeds as follows (refer to Figure 3.14):
   - ☐ Plot a reference signal band for the leftmost signal in the system.
   - ☐ Draw a progression speed line beginning at the start of the main street green interval at the reference signal. This speed line will have a slope (fps) representing the desired progression speed.
   - ☐ Draw a horizontal working line through the center of either a red or green interval for the reference signal.
   - ☐ Center either a red or green signal interval (as required to obtain the greatest width of the through-bands) on the horizontal working line in order to obtain an equal bandwidth for each direction of flow.

44

- ☐ The results of the preceding step will develop a timing plan which will provide equal bandwidths for each direction of flow. This result can then be modified to favor one direction of flow as may be desired.

The manual method just described must be used as a trial-and-error approach. If some of the initial assumptions (such as progression speed, cycle length, cycle splits, etc.) were modified, then a new timing plan could result which might produce better results.

Offline Computer Techniques. Techniques utilizing the calculation power of the digital computer have been developed to compute timing plans for arterial signal systems offline.

The two basic approaches to the problem of computing arterial timing have considered (1) minimizing overall delay and stops, and (2) maximizing the width of the progression band. Hillier of the Transport and Road Research Laboratory in the UK (*24*) developed a delay/difference-of-offsets method for the optimization of offsets in a pretimed signal timing plan for arterials or closed networks. Although the method minimizes delay, it does not necessarily minimize the number of stops or provide uninterrupted progression.

The computational approach which seeks to maximize the bandwidth has perhaps been the most popular for developing arterial timing plans. Research in this area was conducted by Yardeni (*25*), Brooks (*26*), Chamberlain (*27*), Bleyl (*28*), Little, et al. (*29*), Messer, et al. (*30*), and Wallace and Courage (*31*). An excellent overall evaluation of developments in arterial signal system timing has been prepared by Wagner, et al. (*32*).

Several computer models have been developed for arterial signal coordination design. These models can be categorized into two broad categories. The first consists of models that maximize bandwidth (*29, 30*). The second contains models that seek to minimize delay, stops, or other measures of disutility (*24, 33, 34*). The 5 models which will be discussed here in some detail are the following:

- TRANSYT-7F (see subsequent discussion — Closed Network Control)
- SIGOP III (see subsequent discussion — Closed Network Control)
- MAXBAND
- PASSER-II (84)
- AAP-85

MAXBAND — MAXBAND is a bandwidth optimization model that develops signal timing plans for arterials and triangular networks (*35*) The optimization algorithm used in MAXBAND is based on a mixed-integer programming formulation which has been described by Little (*36*). Some of the features of MAXBAND are as follows:

- Cycle length is treated as a continuous variable within a specified range.
- Design speed can vary within specified limits.
- The best phase sequence at each intersection is automatically selected from a specified set.
- Queue clearance time is allowed to permit secondary flow accumulated during red to discharge before the arrival of the platoon.
- The model accepts user-specified weights for the green band in each direction.

Basic inputs to MAXBAND include the range of cycle lengths, geometry of the different links, traffic flow rates, saturation flow rates, permitted phase sequences, queue clearance times, and range of speeds. Outputs include a data summary report and a solutions report that contains cycle length, bandwidths, selected phase sequencing, splits, offsets, link speed, and travel time.

MAXBAND was written in FORTRAN IV for use with IBM 370 computers but will likely be adapted to other computers in the future. It can handle as many as 20 signals efficiently. The documentation of MAXBAND has been prepared by Little and Kelson (*35*); however, experience with it is limited.

PASSER-II (84) Model — The Progression Analysis and Signal System Evaluation Routine (PASSER) is an optimization model for progression along an arterial street considering various multiphase sequences. Further improvements in the processing algorithms and measures of effectiveness have been made by the Texas Transportation Institute, and the current version of the model is known as PASSER-II (84) (*21*).

The PASSER-II (84) model combines Brook's Interference Algorithm with Little's Optimized Unequal Bandwidth Equation, and extends them to multiphase arterial signal operations. The model inputs include turning movements, saturation capacity flow rates, distances between intersections, average link speeds, queue clearance intervals, permissible phasing sequences, and minimum green times that must be provided for at each intersection. The program first determines the optimal demand-to-capacity ratios and uses them to determine the splits. Trial cycle lengths, phase, patterns, and offsets are varied to determine the optimal set of timings which maximizes the progression bandwidth.

PASSER-II (84) can handle up to 20 signalized intersections along a single arterial street, with up to four phase sequences per intersection. It is written in FORTRAN IV for use on 16/32 bit computers and most microcomputers. The program is currently maintained by the Texas Department of Highways and Public Transportation.

AAP-85 — The Arterial Analysis Package (AAP) (*37*) is a collection of existing signal design and analysis programs, most of which are described in previous sections. The TRANSYT-7F model optimizes signal offsets for a given cycle length by minimizing a performance index which is a linear function of stops and delays. The SOAP-84 model determines optimum signal timing (cycle length, splits, and phase sequence) at an individual signalized intersection with either pretimed or actuated control. It also provides dial assignments for multiple time periods. The PASSER-II (84) model calculates cycle lengths, phase sequences, offsets, and splits so that the bandwidth along an arterial street is maximized.

The AAP-85 model package uses a common data base, and input and output formats (some interactive) for all component models to facilitate the use of these models as an integrated system. It provides traffic engineers with a set of easy-to-use analysis programs.

Online Control Techniques. With the availability of high-speed digital computers and an extensive traffic surveillance system, it has become feasible to develop dynamic or real-time timing plans for arterial street systems. The utilization of this concept of control in actual systems, however, is very limited at present.

One concept of real-time control of arterial street systems proceeds by collecting information on traffic conditions with a traffic detection system. This information is then fed to a central location for storage and analysis, which then permits a reasonable prediction of traffic conditions 15 to 30 min in advance based on historical flow data. If a traffic condition can be predicted in advance by such means, then the timing plan can be computed and implemented to meet the predicted conditions.

Of the three methods by which a computer-based signal system exercises control through timing plan selection, the two most important are discussed in the following material.

- Time-of-day control — A strategic timing plan is introduced into operation at a given time of the day in the category time-of-day strategic control. The timing plans might only respond to the three basic time periods such as a.m. peak (7-9 a.m.), off-peak (9 a.m.-4 p.m. and 6 p.m.-7 a.m.), and p.m. peak (4-6 p.m.), or to a great many more time periods.

  Where traffic demand is reasonably predictable, coordinated pretimed controllers can provide satisfactory operations. Where one or more intersections require multiphase operation, full-actuated controllers can be incorporated into the coordinated system. Such systems are available at present from traffic signal manufacturers through use of state-of-the-art equipment. A typical system can provide up to four cycle lengths, three splits per cycle length, and three offsets per cycle length. Present hardware technology now permits traffic pattern changes to be made by downloading new patterns from a central system master into a microprocessor-based local controller. A detailed discussion of local controllers and system masters is provided in Chapters 6 and 7, respectively.

- Traffic-responsive control — In traffic-responsive control, the strategic timing plan is based upon traffic conditions which are measured through a traffic-detection system. With this approach, timing plan updates can occur as often as every cycle. Computer control systems of this type are referred to as either "table look-up" or "pattern generation systems."

If the response period for changing the signal timing can be shortened to a cycle length or less, then the control concept could be classified as being in the tactical control category. Some control systems which could be classified in this control category include the following:

- The DARTS System — The Dynamic Artery Responsive Traffic Signal System (DARTS) consists of a series of NEMA full-actuated controllers, each with an external logic modular dynamic coordination unit (*38*). The system allows each intersection to function in its normal isolated full-actuated mode until a platoon is detected along the arterial at an intersection. Once a platoon is detected, the upstream intersection controller advises the adjacent downstream intersection controller that a platoon is on the way. Through the use of three timers, the adjacent downstream controller coordination unit permits the cross-street and opposing left-turn phases to occur (if there is a demand) and then forces off these phases in time for the arterial street platoon to pass through the intersection (*38*). If the cross-street and/or left-turn demand is not fulfilled for a period of time at an intersection, then this intersection is dropped from the coordinated system for one cycle to permit clearance of traffic on all phases. The system utilizes two pairs of wires between intersections, one pair for each direction of travel. The DARTS system was developed by the

Texas State Department of Highways and Public Transportation and has been successfully implemented.

- The FACTS System — Another system developed by the Texas Department of Highways and Public Transportation is the FACTS system which stands for Flexible Advanced Computer Traffic Signal System (*38*). This system has been developed for use along arterial highways, freeway frontage roads, complex freeway interchanges involving traffic signals, and small grid networks. It utilizes a minicomputer which can provide for individual phase control of 24 intersection controllers assigned to 4 sections for CIC or critical section control. The computer utilizes the hold, phase omit, and force-off inputs of the NEMA controller unit to provide any desired left-turn sequence of operation. The use of these command functions also permits unutilized time from the actuated cross-street and left-turn phases to be allocated to the main street phases so as to improve the overall intersection operation and the arterial street progression. A 1½-generation system control has been developed for the arterial street design using the PASSER II (84) model for pattern development. The 1½-generation control concept is discussed later in this chapter.
- Actuated controllers with background cycle — In an effort to obtain good progression and also to retain traffic-responsive control at each individual intersection, interconnected actuated controllers with a background cycle have been utilized. This system utilizes detectors on the side streets at each intersection, but using force-off inputs it permits the side streets to receive a green indication only when it will not interfere with progressive movement on the major arterial. This concept provides for a predetermined minimum through-band along the coordinated arterial by establishing a preset point (yield point) in the background cycle when vehicle calls on the side street can be serviced. In the absence of demand on the side streets (as measured by detectors), the green assignment will remain on the major arterial.
- Online timing-plan generation — Two types of approaches can be considered in defining the online timing plan generation control concept. First, it is possible to consider an approach which uses a predictive algorithm procedure and computes a desired timing plan on a cycle-by-cycle basis. Difficulty is encountered with this approach when one considers the complex problems associated with accurate prediction of traffic patterns, making the timing plan calculations, and implementing them on a cycle-by-cycle basis. Speed of computation becomes critical, and the problems of transitioning from one timing plan to another are exacerbated because of the frequency of change.

  A second approach to be considered in providing tactical control for arterial signal systems may be the technique of utilizing both a background cycle and traffic-responsive control at each intersection. A background cycle length and offset relationships at each intersection are established. Detectors are then utilized to monitor traffic on all phases at each signalized intersection and green time is allocated as needed. Phase skipping and phase shortening are utilized to a maximum, and the green time thus gained is transferred to the major arterial movement. The maintenance of the desired offset relationships (background cycle), however, is continuously respected in order to facilitate progressive flow on the main arterial.

  The progression-band directional preference is changed (inbound, off-peak, outbound, etc.) as required, and the system is programmed to change modes from system control to isolated control, as dictated by traffic conditions.

  Closed loop system — The closed-loop concept embodies two-way communication, an intelligent microprocessor master, intelligent monitors at local intersections, and the ability, through standard dial-up phone line and modems, to monitor and control the system from a central office computer. This signal system control technique is discussed in detail in Chapter 7.

Isolated vs. System Control. Early thinking on the subject of signal control for arterial streets almost always indicated the need to interconnect signals into a single system and to work toward maximizing progressive movement. It may be helpful to identify the various factors that affect arterial street signal timing and to indicate their potential impact on the basic control strategy to be utilized.

Basic factors that should be considered include the following:

- Distance between signalized intersections — The spacing of signalized inter sections on an arterial street may range from 150 ft to more than 5,000 ft. The need to operate the signals as a system generally increases as the distance between signals decreases. However, optimum operation can be attained at greater distances.
- Street operation — One-way vs. two-way — One-way street operation greatly facilitates progressive movement and lends emphasis to system control.
- Signal phasing — The type of intersection under control relative to signal-phase requirements also influences system control. Some arterials have rather

47

simple two-phase intersections, while other arterials require multiple left-turn phases.

- Arrival characteristics — The arrival characteristics of traffic at the signalized intersections are also important. Conditions which tend to create random, unplatooned vehicle arrivals include the following:
    - Excessive distances between signalized intersections
    - High volume of traffic turning onto the arterial from minor streets or access points (e.g., shopping center) between two signalized intersections
    - High volumes turning into the arterial from the minor street approaches at the signalized intersections
- Traffic fluctuations with time — The arrival characteristics and traffic flow conditions, of course, vary greatly during the 24-hr of the daily time period. Peak period conditions may strongly indicate the need for system operation, but off-peak conditions may best be handled with isolated or flashing control.

3.9 CLOSED NETWORK CONTROL

The previous section on arterial street control discussed what is often referred to as an open network control.

In the case where two arterials cross at a single intersection, a signal timing interlock must occur at that intersection. The same cycle length must be utilized for both arterials, and the timing plans must be developed, using as a reference point the timing at the intersection where the arterials intersect.

If arterial streets cross and form a closed network, as shown in Figure 3.15, then the timing plans must interlock at all four intersections (A, B, C, D). These types of signal networks occur most frequently in the central business districts (CBD) of cities.

Basic Concept

The basic concept of signal timing for closed networks that has prevailed for many years is one of attempting to provide progression along any street in the network. For example, in Figure 3.15, this concept could be translated to the objective of providing for progression on streets AB, BA, BD, DB, CD, DC, CA, and AC (assuming 2-way flow on all streets).

For a typical network, such as shown in Figure 3.15, a time-space diagram for this signal network could be developed as shown in Figure 3.16. From the example data in Figure 3.15, it is possible to develop a relationship among signal cycle, green intervals, and offsets, as follows:

$$nc = T_{ab} + P_{bf} + T_{bc} + P_{ch} + T_{cd} + P_{dm} + T_{da} + P_{as} \qquad (3.27)$$

Where:

n = An integer number
c = Cycle length
T_{ab} = Offset between signal A and signal B
P_{bf} = Green interval on Franklin Street at intersection B
T_{bc} = Offset between signal B and signal C
P_{ch} = Green interval on Howard Street at intersection C
T_{cd} = Offset between signal C and signal D
P_{dm} = Green interval on Mulberry Street at intersection D
T_{da} = Offset between signal D and signal A
P_{as} = Green interval on St. Paul Street at intersection A

It can be seen that the equation will be valid if the summation of the offsets and the summation of the green intervals add up to some multiple of the cycle length. This explains the common use of 50-50 phase splits and zero-, half-, or quarter-cycle offsets.

This concept of timing works well for a rectangular or square grid network where the block lengths are long enough to permit a half-cycle offset for two-way operation or a quarter-cycle offset for one-way operation. As the street system deviates from a grid network with desired block lengths, the efficiency of the signal timing deteriorates. The use of 50-50 splits at all intersections may also introduce delay or congestion.

The cycle length and phase lengths are related to traffic capacity requirements and to pedestrian crossing times. A common cycle length is a prerequisite of the concept.

The control system can be made somewhat responsive to traffic flow by changing the cycle length (which may affect splits and offsets). This can be done on a timeclock basis (such as for a.m., off-peak, and p.m.) or on the basis of traffic detection.

Preferential Control

In order to move peak-period traffic, it may be desirable to create open signal networks and to favor traffic flow on selected streets. For peak-period flow it might be desirable to consider only selected streets for the purpose of signal timing. Desirably, these streets would form an open network, as shown in Figure 3.17. The selection of

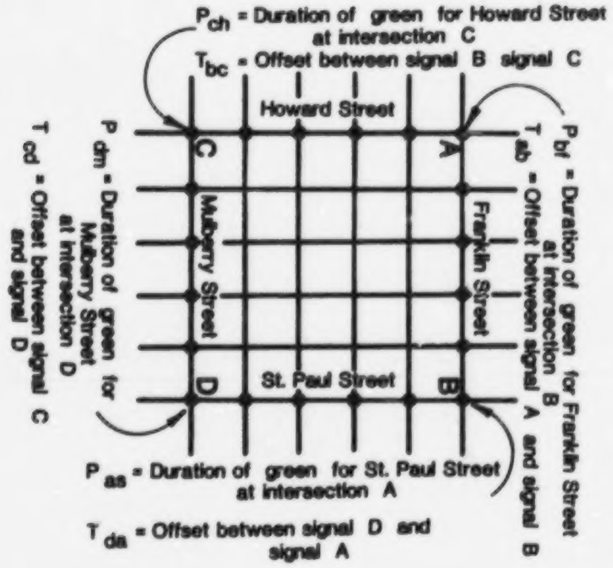

P_{ch} = Duration of green for Howard Street at intersection C
T_{bc} = Offset between signal B signal C
Howard Street
C
A
Mulberry Street
Franklin Street
St. Paul Street
D
B
P_{bf} = Duration of green for Franklin Street at intersection B
T_{ab} = Offset between signal A and signal B
P_{dm} = Duration of green for Mulberry Street at intersection D
T_{cd} = Offset between signal C and signal D
P_{as} = Duration of green for St. Paul Street at intersection A
T_{da} = Offset between signal D and signal A

Figure 3.15. Typical signal network

the specific streets to form the open network would, of course, be dependent upon the origins and destinations of the traffic and the configuration of the street facilities. By developing the open network, it then becomes possible to utilize open network timing, and to facilitate the selected movements.

Timing Plan Development

In considering the state of the art relative to control concepts for closed networks, it is possible to summarize the various methods for developing timing plans in the same manner as previously discussed for arterial streets. These methods are as follows:

- Manual techniques
- Computer techniques (offline)
- UTCS Control techniques (real-time)

Manual Techniques. The use of graphical trial and error techniques in a bandwidth approach to developing timing plans for a closed network is very difficult. A 3-dimensional time-space diagram is actually needed if one is to consider flow in all directions at the signalized intersections.

If the signal network is in a grid pattern, the common technique has been to utilize the basic concept of closed network timing and utilize timing plans of the following type:

- Simultaneous — Timing plan where a zero offset is used for several consecutive signals, along with a 50-50 cycle split.

  This system is utilized where extremely short block lengths occur and also where saturated flow conditions exist.

- Single alternate — Timing plan with half-cycle offsets that are alternated at each signal.

  This timing plan works well if the block lengths and/or cycle length permit the use of a half-cycle offset. For example, with a 60-sec cycle and a half-cycle offset, the offset is 30 sec. If the block length is 900 ft, then a progression speed of 900/30 = 30 fps is obtained.

- Double alternate — This is a variation of the single-alternate technique where two adjacent signals have the same offset and a half-cycle offset occurs every two signals.

This system is often used for block lengths in the range of 450 ft. It should be noted, however, that the width of the through-band is reduced to one-half that of a single-alternate system. If the block lengths are shorter, a triple-alternate system might be utilized.

- Quarter-cycle offset — A common timing plan used when a 1-way signal grid exists is the quarter-cycle offset.

  This timing plan works well with block lengths of approximately 450 ft. For example, with a cycle length of 60 sec, the progression speed would be 450/15 = 30 fps.

It can be concluded that all of the timing plans that have been discussed are very dependent upon the geometrics of the grid network (specifically block length) and are very inflexible. With this timing approach, the only variables are the cycle length or type of plan (single alternate, double alternate, etc.).

Computer Techniques. A number of algorithms and computer models have been developed with the objective of aiding a traffic engineer in the design of signal timing plans for cycle-based, pretimed control of traffic signal networks. These algorithms and programs were developed to function offline (as opposed to real-time or online).

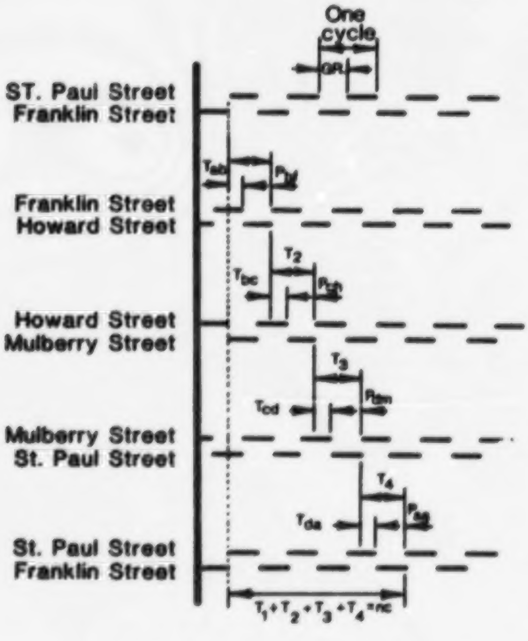


Figure 3.16. Closed network signal timing

Computer techniques for offline signal timing plan computation that are well documented and have received considerable testing and application include the following:

- TRANSYT-7F Model
- SIGOP-III Model

A relatively brief overview of these methods will be presented in the following material in an effort to acquaint the reader with the basic state of the art in this area of traffic control. A considerable amount of documentation is available on most of these methods and will be referenced for the reader who desires to gain further knowledge of a given method.

TRANSYT-7F Model — The Traffic Network Study Tool (TRANSYT) is one of the most widely used models in the United States and in Europe for signal network timing design. It was developed in 1968 by Robertson (*34*) of the Transport and Road Research Laboratory (TRRL) in England, and since then, the TRRL has released several versions of this model. The version which is discussed here is TRANSYT-7F, where "7" denotes the seventh TRRL version of TRANSYT, and "F" symbolizes that this is the Federal Highway Administration's version of TRANSYT-7 which uses North American nomenclature on input and output (*21*).

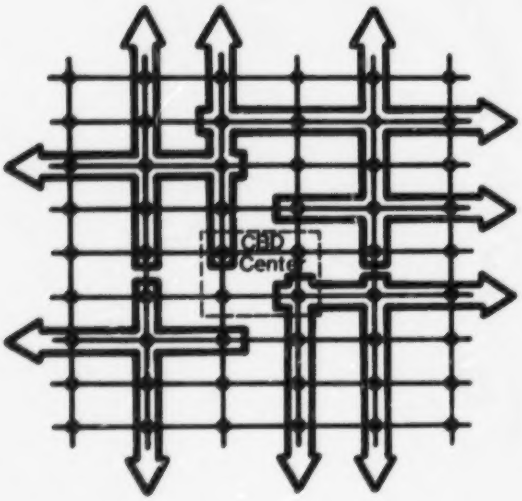


Figure 3.17. Preferential flow

TRANSYT-7F is used to optimize signal timing on coordinated arterials and grid networks. The mode of signal control considered by TRANSYT-7F is pretimed, with 2 to 7 phases and fixed-phase sequence.

The structure of TRANSYT-7F consists of two main parts:

- A macroscopic, deterministic traffic flow model which is used to compute the value of a specified performance index for a given signal network and a given set of signal timings. The performance index is a linear combination of measures of effectiveness (delays and stops) which are specified by the user.
- A hill-climbing optimization procedure which makes changes to signal timings (splits and offsets) and determines whether or not the performance index is improved.

TRANSYT-7F has a number of options which can be controlled by the user. These options include the following:

- Buses can be modeled separately by including bus links. These can either be separate lanes or shared lanes.
- RT/LT delays caused by pedestrians can be reflected.
- Large networks can be subdivided into sections that can be handled by the program (i.e., 50 nodes and 250 links). The boundary nodes are fixed from section to section so that their timings are not changed in the subsequent analysis. Another alternative is the expansion of program dimensional arrays to accommodate the larger network.
- Unsignalized intersections controlled by stop signs on the cross-streets and bottle necks can be modeled.
- An estimate of network fuel consumptions can be computed based on total travel, stops, and delay. The fuel consumption value includes fuel consumed at cruise, idle, and acceleration or deceleration. Fuel consumption estimates are calculated for each link and then summed for the entire network.

The TRANSYT-7F model is written in FORTRAN IV for 16- or 32-bit computers and is available for most microcomputers. A comprehensive user's manual was written to serve as an instructional guide for traffic engineers who desire to use the model (*39*).

SIGOP-III Model — SIGOP-III is an acronym for Traffic Signal Optimization Model, Version III. It was developed by KLD Associates, Inc., as an outgrowth and refinement of the original SIGOP model developed in the mid-1960s (*40*). The similarities between TRANSYT-7F and SIGOP-III are: (1) both models are macroscopic signal timing and analysis tools, and (2) both models contain a traffic flow submodel and an optimization submodel which minimizes a user-specified "disutility" function. TRANSYT-7F considers delay and stops, whereas SIGOP-III considers delay, stops, and a term for queue "spillover" (*41*).

The basic inputs to SIGOP-III include flow rates, saturation flows (in terms of headways), minimum green times, yellow times, special phase times, and passenger car equivalent factors for trucks, buses, and turning vehicles (*21, 41*). Outputs include: (1) data summary report, (2) signal timing report which contains offsets and splits for each phase, (3) performance analysis report which shows the value of the disutility function for each iteration of the model including the optimal value and detailed performance measures for each link and for the network as a total, and (4) user-specified time-space plots.

SIGOP-III is written in FORTRAN IV for use with IBM 360/370, CDC 6600, and Amdahl 470 computer systems. Although limited to 80 signals and 230 links, the model documentation describes how it can be expanded to handle larger systems.

Like many signal timing computer models, SIGOP-III has advantages and limitations. One of the major advantages of this model is the multiple cycle-length evaluation capability which can save the designer a considerable amount of time that would ordinarily be spent in preparing and running several jobs. The major limitations of SIGOP-III include the following (*21*):

- Each signal cycle can accommodate a maximum of four phases which does not adequately serve some users.
- The model does not consider bus links.
- Permissive and unprotected turns are not addressed explicitly by SIGOP-III. However, these conditions can be allowed for to some extent by restricting the capacities of such movements.
- The model does not explicitly consider nonsignalized intersections (stop sign control, for example).
- The model lacks extensive field testing and evaluation.

Experience with Offline Models — Both SIGOP-III and TRANSYT-7F models represent the latest state-of-the-art. During 1981, TRANSYT-7F was tested in 11 cities in the United States where it was used to produce optimal signal timing plans for a total of 520 intersections in coordinated signal systems. These cities contracted with the FHWA to undertake a project to optimize the signal timing in a portion of their street network and to evaluate the effectiveness of the optimized signal timing plans. Although the preliminary evaluation data are limited, the cities reported unanimous agreement on the positive value of the TRANSYT-7F model for use in retiming traffic signal systems (*42*).

UTCS Control Techniques. The development of efficient and effective real-time traffic control systems might be termed the ultimate objective of the traffic control engineer. The achievement of this objective is difficult and research work in this area represents one of the leading edges of the traffic control field.

State-of-the-art concepts of traffic-responsive control in urban street networks consist mainly of the three generations of the Urban Traffic Control System (UTCS), in addition to other systems which utilize microprocessor-based controllers for developing on-line control strategies. The UTCS project was established by the Office of Research of the Federal Highway Administration in the early 1970s to provide for computer-supervised control of 200 signalized intersections in Washington, D.C. An excellent overview of this project can be obtained from the publication, "The Urban Traffic Control System in Washington, D.C." (*43*)

The UTCS research project on control strategies has been divided into three generations of traffic control techniques, usually referred to as 1-GC, 2-GC, and 3-GC. These techniques are briefly described as follows:

First-Generation Control (1-GC) — First-generation control uses prestored signal timing plans developed off-line and based on historical traffic data; the system is capable of storing up to 40 timing plans (*44*). The plan controlling the traffic system can be selected on the basis of time-of-day, by direct operator selection, or by matching from the existing library a plan that is best suited to recently measured traffic conditions. The matching criterion is based on a network threshold value which incorporates traffic volumes and occupancies. The mode of plan selection is determined by the operator.

In the traffic-responsive mode, timing plans are usually updated once every 15 min. Smooth transition between different timing plans is provided by a transition routine which is part of 1-GC. This routine evaluates the magnitude of the changes, determines the time required for a smooth transition, and then controls signal timing settings until the transition is complete. The same procedure of control is used for transition between computer control and standby.

The pattern in effect is enhanced by a critical intersection control (CIC) feature, which is used to fine-tune the system at intersections which saturate frequently, by adjusting the allocation of green time (split) based on fluctuations in local traffic demand.

Certain intersections may be instrumented for bus priority. The decision to grant additional green time to buses is a function of passenger volumes, vehicular queues in and around the intersection, and the time of the arrival of a bus on the approach to the intersection. The program logic which makes this decision is contained within the BPS algorithm. The algorithm analyzes the actual intersection conditions in real-time and adjusts the signal cycle splits in response to actuated demands.

Timing plans for 1-GC can be calculated using one of the offline computer software models described earlier; TRANSYT-generated plans were selected for testing in the UTCS research project in Washington, D.C.

Second-Generation Control (2-GC) — As an alternative to the stored library of signal timing plans used by 1-GC software, 2-GC was developed as an online model that computes and implements signal timing plans in real-time based on surveillance data gathered from vehicle detectors and predicted traffic volumes (*44*). The software of 2-GC contains an online optimization routine (which employs the optimization algorithm of the SIGOP model discussed earlier) to determine the control parameters that will minimize the total delay and stops within the network under current traffic conditions. The optimization process can be repeated at 5- to 10-min intervals whenever traffic conditions have changed enough to justify the computation of a new set of control parameters.

Additional sophistication is also provided for the second-generation critical intersection control. This routine will vary not only the signal split as in the case of the first-generation software, but the relative green times between intersections (offsets) are also adjusted on a cycle-by-cycle basis to provide additional responsiveness to short-term fluctuations in traffic volumes.

Second-generation software also has the capability for dynamically decomposing the network into sections (subnetworks) on the basis of traffic conditions. The optimum timing patterns are then computed for individual sections, and the sections are interfaced to assure smooth traffic progression across the subnetwork boundaries.

A number of other routines are contained in the second-generation software that are designed to improve flow within the network, including an improved transition routine, a prediction capability, and software to estimate traffic conditions at intersections that are not instrumented with vehicle detectors. The second-generation control package is known as TANSTP which stands for Traffic Adaptive Network Signal Timing Program (*44*).

Third-Generation Control (3-GC) — This control strategy is a significant departure from the 1-GC and 2-GC in that it was conceived to implement and evaluate a fully traffic-responsive, on-line control system. To accomplish this goal, 3-GC was designed to allow the signal timing parameters to change continuously in response to real-time measurements of traffic variables. The time period between timing plan revisions were usually in the magnitude of 3 to 5 min (*44*). Numerous problems associated with instrumentation (and associated maintenance) and transition-related deficiencies forced the discontinuation of this work, and no work is currently planned in this area.

A comparison of the basic features of the two UTCS generations is shown in Table 3.3. Each control generation was designed to provide an increased degree of traffic responsiveness. The 2-GC technique can be termed a cycle-based control strategy since a common cycle length is used within variable groups of intersections.

Prediction of traffic volumes, occupancies, and speeds on each link of the street network is critical to the effectiveness of the timing plans determined by the 2-GC technique. The prediction models must be capable of providing accurate forecasts of traffic variables that will exist during the time when the new timing plan is in use based on data that has been collected during previous time periods. Errors in the prediction process can seriously degrade the performance of the implemented timing plan, particularly in the case of 2-GC where the advanced time for prediction is greater than 5 min.

UTCS First-Generation Enhanced and Extended — In cooperation with industry, the Federal Highway Administration decided to incorporate the proven functions of the original 1-GC software into an enhanced software package that would be compatible with the 16-bit and 32-bit minicomputer traffic control systems in current use, as well as the system configurations that could be anticipated through the 1980's. The proposed enhancements came as suggestions during a conference of the FHWA and industry in June 1975. The conference resulted in the UTCS Software Implementation Support Program which has been conducted by Honeywell, Inc., and A. M. Voorhees and Associates for the FHWA. The objectives of this program have been to minimize the costs and increase the reliability and operational performance of digital computer traffic control systems for the states and municipalities by standardizing the software and improving and supporting the FHWA-developed control programs.

The UTCS first-generation Enhanced and Extended has been developed to include the following features (*45, 46*):

- New capabilities — The new capabilities incorporated into the extended 1-GC involve:
    - Data base management — The new software provides a complete data base management capability. Operator interface is implemented with an operator interface language (OIL), which uses traffic engineering terminology. The software will enable the operator to change any parameters that are dynamic in nature. Data base management also includes a capability for offline development of software system configuration.
    - Controller assemblies — Commands to actuated

Table 3.3. Comparison of UTCS control techniques

Feature	First Generation	Second Generation
Optimization	Offline	Online
Frequency of update	15 min	5-10 min
Number of timing patterns	Up to 40	Unlimited
Traffic prediction	No	Yes
Critical intersection control	Adjusts split	Adjusts split and offset
Hierarchies of control	Pattern selection	Pattern computation
Fixed cycle length	Within each section	Within variable groups of intersections

Source: Reference (*43*)

controller assemblies are expanded and an interface with microprocessor-based controller units is provided. Controller modes include flashing operation and special function commands. Intersections which are preempted locally are accounted for, and intersections with similar traffic patterns can be grouped automatically into sections or subnetworks.

  - Actuated controller operation — The system is capable of handling either the coordinated or noncoordinated control modes of actuated controllers, including both single ring and dual ring controllers. In the coordinated control mode, the software issues force-off and yield commands in the background cycle. In the noncoordinated mode, the system only monitors the actuated controller for proper operation.
  - Green returns — Controllers which transmit more than one phase return indication are monitored for test and display purposes.
  - Stops, delays, and queue computation — New methods of estimating stops, delays, and queue lengths using one detector per approach are incorporated into the software.
  - Map display — Map display capability is expanded by adding displays of multiple-phase intersection green, transitioning intersections, preempted intersections, flashing intersections, congestion, and advance, yield, and force-off commands.
  - Input devices — Commands and data can be entered from any input peripheral.
  - Section (Subnetwork) synchronization — It is possible to lock adjacent sections (subnetworks) together, causing them to operate on a common cycle length.
  - Communications protocol — The software supports time division mutliplex, frequency division multiplex, and direct wire communications techniques. These techniques are discussed in detail in Chapter 8.
  - Unattended operation — The software permits system operation in an unattended mode which uses automatic scheduling and monitoring of system functions. Also, a software interface for indicating system hardware failures is provided for sounding alarms and printing messages to alert personnel that corrective action should be taken.
  - Time-space diagram — The software includes a capability for producing time-space diagrams in the offline or background mode.
  - Application flexibility — The software is organized by functions and modules to enable configuring systems that meet specific application requirements. Increases or decreases in functional capability is accomplished by adding or deleting specific program modules.

- Enhancement of original capabilities — The basic enhancements to the 1-GC capabilities include:
  - Controller monitoring and control — The software's capability of monitoring and controlling actuated controller operations are increased.
  - Signal timing plans — The software associates timing plans with individual controllers, thus allowing any combination of intersections to operate as a subsystem or section.
  - Time-of-day/day-of-week — The software is capable of assigning an operator command to a specific TOD/DOW file, thus allowing commands to be issued automatically.
  - Transitioning — The software is capable of providing rapid transitions from one timing plan to another within minimum or maximum constraints imposed on the transition cycle length. Transition begins at main street green by implementing the new timing plan's cycle length and split. The offset transition is accomplished either by contracting or expanding phase times until the current offset equals the new intended offset.

- System functional components — The major functional components comprising the enhanced 1-GC software are described below:
  - Detector telemetry processing — This function involves processing detector surveillance inputs to compute vehicle presence durations and perform reasonableness checks to assure that the computations of measures of effectiveness do not include inputs from malfunctioning detectors. It automatically drops failed detectors and returns functional detectors to the online mode of operation.
  - Measures of effectiveness algorithms — Vehicle presence pulse durations together with data defining the times of their occurrence are processed by measures of effectiveness algorithms to provide traffic volume, speed, occupancy, stops, delays, queue length, demand per signal cycle, and congestion. (A discussion of measures of effectiveness is presented at the end of this chapter.)
  - Operator interface language (OIL) — The OIL uses common traffic engineering terms and is structured to facilitate an interactive, conversational mode from a standard CRT or typewriter

terminal. The OIL enables an operator to alternately interrogate the system and receive answers, and to direct the system operation.

- Communications processing — A modular communications software package provides for compatibility with different types of communications hardware.
- Controller operations — This function provides for direct computer control of each intersection in the system, transferring a local controller from standby control to online control, advancing a controller through predetermined intervals and phase displays, and transferring a controller from online control to standby control.
- Manual plan selection — This function permits an operator to select any signal timing plan for one or more controllers. In responding to this type of operator's request, the software performs data validity checks and then implements the selected plan.
- Time-of-day/day-of-week operation — This operation identifies specific timing plan schedules for specific times of day, specific days of the week, and for special days or events. These schedules are alterable by operator command on either a temporary or permanent basis.
- Traffic responsive operation — Input data from vehicle detectors is used to select a timing plan from a library of stored plans.
- Critical intersection control (CIC) — The CIC function is used at an individual intersection when it is properly instrumented with vehicle detectors and one or more of the intersection approach volumes exceeds a specified input threshold value.

Since August 1979, the 1-GC enhanced software has undergone extensive testing in Broward County, Florida. The testing program involve 52 intersections and was designed to evaluate and validate the operability of the new software (*47*). Further testing has been completed in the Birmingham, Alabama, system.

UTCS 1½-Generation Control — As discussed earlier, the UTCS first-generation control utilizes prestored library of signal timing plans which are calculated offline based on historical data. The timing plan to be implemented is selected on the basis of time-of-day, direct operator commands, or by matching from the existing library a plan best suited to recently measured traffic conditions. Cities which used 1-GC were faced with the problem of developing a full complement of suitable timing plans to accommodate the various traffic patterns that may arise in each control section within an areawide control system. The burden of properly discharging this obligation was overwhelming; several hundred timing plans were often required when the number of control sections and the number of different traffic patterns were properly enumerated.

FORCAST — FORCAST is a computer software model that was developed by Computran Systems Corporation for the purpose of generating timing plans for signalized intersection networks. It is designed for online usage with a combination of UTCS 1-GC and a proprietary software traffic control package to facilitate the generation and maintenance of the timing plans library (*48*).

The structure of FORCAST permits an interactive search for optimum timing plans over a range of cycle lengths. In this process, each of the permitted cycle lengths is examined and a best timing plan is developed for this cycle length. Phase sequences, green times, change times, and clearance times are stipulated in the FORCAST input in accordance with their settings on the controllers. The optimization logic used by FORCAST involves sequential threading of prescribed movements through the network using a priority listing of demands to be accommodated (*49*). During this threading process, FORCAST adjusts in a priority manner the individual splits and offsets of each intersection in order to accommodate the defined movements throughout the network. The optimization criterion is a function of stops and delays. Once the optimum solution has been identified by FORCAST, the corresponding timing plan for this solution is output for the user in the form of cycle length, offset, and interval time for the intersections (*49*). Time-space diagrams for the selected timing plan can also be produced based on user's request.

Many cities used versions of TRANSYT and SIGOP models as timing plan generation software, but the task of assembling and inputting data was complex, burdensome, and required very competent staff. Therefore, it was not uncommon to find that many computer-supervised signal control systems were functioning with a small number of relatively crude timing plans (*49*). Most often these plans were developed shortly after system implementation and have not been revised for a substantial period of time.

To overcome the problems resulting from an inadequate number of improperly maintained timing plans, it was necessary to develop a simple procedure for generating and maintaining an adequate library of appropriate timing plans. One way to accomplish this objective is to use an online timing plan generator with automated loading of the generated plans into the traffic control system.

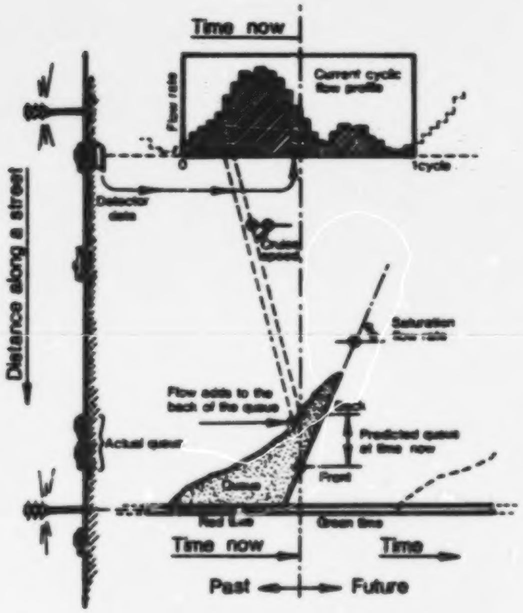


Figure 3.18. Principles of the SCOOT traffic model

Source: Reference (*50*)

This concept, which has been referred to as 1½-generation control, was implemented in the City of Winston-Salem, North Carolina, in 1981. Program FORCAST was used to generate online timing plans for 1-GC. In this implementation, optimal timing plans can be generated for sections of 50 intersections while the system is online and operating a total of 209 intersections. The system user evaluates the suitability of the generated plan based on the output measures of effectiveness and time-space diagrams. If the resultant output is acceptable, the timing plan can be loaded into the system library.

The overall impact of using FORCAST along with 1-GC in the Winston-Salem signal control system has made the city staff more able to contend with the normal operating problems inherent in the long-term operation of the control system (*49*).

While the UTCS was being developed and tested in the United States, parallel efforts and experiments were being made in Great Britain, Canada, and Japan to develop online, traffic-responsive control techniques for street networks. The British experiments were conducted by the Transport and Road Research Laboratory and led to the development of Split, Cycle, and Offset Optimization Technique (SCOOT). A brief description of the SCOOT technique is provided below.

Split, Cycle, and Offset Optimization Technique (SCOOT) — The TRRL started its development work on SCOOT in 1973, and by 1979 this technique was implemented on a full-scale trial project in Glasgow. A further full-scale trial of the developed system was carried out in the City of Coventry in 1980 (*50, 51*).

Based on traffic surveillance data obtained from vehicle detectors, SCOOT determines the best scheme for coordinating adjacent pairs of signals as well as the optimal timing plan. For each link, the SCOOT model predicts the current value of the vehicle queue at the stopline using real-time information on cyclic flow profiles. Figure 3.18 illustrates this concept. A few seconds before each change in the current timing plan, the online split-optimizer built in SCOOT estimates whether it is better to make the change earlier, as scheduled, or later. The split-optimizer implements whichever alteration will minimize the maximum degree of saturation on the approaches to a particular intersection. Any alteration made to the green time is temporary, and for each temporary alteration, a smaller permanent alteration is made to the signal timing plan.

Another online algorithm built in SCOOT, and known as the offset optimizer, operates on each intersection, each signal cycle. The information on the cyclic flow profiles is used to estimate whether or not an alteration to the offset will improve the overall traffic progression on those streets which are immediately upstream or downstream of the intersection under consideration. The objective function to be minimized includes delays, stops, and congestion (*50, 52*).

The SCOOT model employs a common cycle length for each section (subnetwork) of signals in order to maintain coordination between signals. A cycle time optimizer can vary the cycle length for each section in increments of a few seconds at intervals of not less than two and one-half minutes. Each section cycle is varied independently of other section cycles between preset upper and lower limits. SCOOT varies the cycle length to ensure that the most heavily loaded junction operates, if possible, at a maximum degree of saturation of 90 percent.

Experience with Control Techniques — Experimentation with online computer control techniques for urban street networks was conducted during the past 15 years in the United States, Great Britain, and Canada. The following material provides a summary review of the experience gained from these experiments.

- The American experience — At the present time, many computer-supervised control systems operate using the first-generation of UTCS control concepts. The UTCS 2-GC generation which was originally developed in Washington, D.C., is operational in Overland Park, Kansas. No other operational 2-GC installation exists in the United States. Variations of 2-GC concept have been developed in Great Britain and Australia, and some encouraging evaluation results have been reported by these systems. The third UTCS generation has not been fully evaluated because its extensive surveillance requirements exceeded the capabilities of the UTCS system. For this reason, this strategy requires additional research and development before it can receive serious consideration as a candidate for operational implementation.

Experimentation with 1-GC has indicated that, in its various modes of operation, it performed best overall and demonstrated that it can provide some measurable reductions in total travel time over that which could be attained with a well-designed pretimed system (*53*). The pattern-matching mode of 1-GC plan selection is generally more effective than the time-of-day mode (*53*). The UTCS second generation showed mixed results during its limited evaluation. Overall it was inferior as compared to 1-GC; however, it demonstrated some small improvements on the arterial street level, but degraded traffic flow in the network.

- The British Experience — The TRRL experiments conducted in Glasgow in the early 1970s have led to results that are very similar to those obtained from the UTCS project in the United States. The conclusion was that there was a need for more research and development in this area (*50*). In 1976, the success of the research phase of the SCOOT project led to further developments which involved cooperation between the government and the industry. The implementation phase of SCOOT started in 1979 where it was used to control a network of 40 signals in Glasgow's CBD. The results of SCOOT were compared with a new prepared TRANSYT fixed-time system. Averaged over the day, there was a 6 percent reduction in journey time. The benefits obtained by SCOOT varied considerably during the day as shown in Table 3.4. The greatest demand occurred during the evening peak, though the longest average travel times occurred in the off-peak period when on-street parking and loading and a high proportion of heavy trucks resulted in a reduction in network capacity (*50*). It was at these conditions, when congestion was worst, that SCOOT was the most effective (*50*).

Further testing of SCOOT was conducted in Coventry in 1980. Table 3.5 summarizes the results of SCOOT and TRANSYT. Averaged over the working day, SCOOT resulted in a 5.5 percent reduction in journey time (*50*).

- The Canadian experience — Four control strategies were evaluated in Metropolitan Toronto and compared with an existing strategy which was based on an arterial preference method called SIGRID (*54*). The first three strategies were variations of the 1-GC type, while the fourth was a 2-GC strategy named RTOP for Real-Time Optimization Program. Field evaluations were conducted in a CBD arterial-based section

Table 3.4. Results of SCOOT in Central Glasgow

Feature	a.m. Peak	Off-Peak	p.m. Peak
Average distance travelled (veh km/hr)	3993	3769	4456
Fixed time	245	302	263
Travel to time (1 km sec)			
SCOOT	248	280	248
Improvement of SCOOT (percent)	-1	7[a]	6[a]

[a]Statistically significant at the 95 percent level

Source: Reference (*50*)

Table 3.5. Results of SCOOT in Coventry

Feature	a.m. Peak	Off-Peak	p.m. Peak
Average distance travelled (veh km/hr)	5,228	4,661	5,841
Fixed time	135	123	151
Travel to time (1 km sec)			
SCOOT	128	118	139
Improvement of SCOOT (percent)	5	4[a]	8[a]

[a]Statistically significant at the 95 percent level

Source: Reference (*50*)

(subnetwork) of signals and in a suburban section of signals. Results of the Toronto studies are reported in Table 3.6. These results indicate that among the 1-GC strategies, timing plans generated off-line by computer methods were slightly superior, while the RTOP technique gave mixed results.

- Summary — Online computer control of urban street networks has been the subject of extensive research and development efforts and it represents one of the leading edges of the traffic control field. Simulation studies have indicated that if, under ideal conditions, complete information on vehicle arrivals was available, traffic-responsive control strategies could reduce the delay incurred by using existing nonresponsive strategies by as much as 50 percent (*55, 56*). The requirements for the development of an effective traffic-responsive control system are discussed by Gartner (*57*). Microprocessor-based systems which utilize control strategies such as those described by Miller (*58*), or those used in SCOOT (*50*), SCAT (*59*), and OPAC (*60*) represent new concepts which could enhance the state of the art in online control techniques.

Simulation Models

The development of effective traffic control systems and strategies requires the ability to predict the response of the traffic environment to the implemented control. Simulation provides a powerful tool for gaining enough knowledge of this response for virtually all network configurations, traffic conditions, and control policies. Although the term "simulation" is used to refer to an experiment performed on an artificial model of a real-world system, the preponderance of current simulations makes use of digital computers to implement the models.

The reasons for using simulation to test traffic control systems and strategies include the following (*61*):

- The need to evaluate the behavior of a new control system or operating procedure prior to its actual implementation because:
  - ▫ The implementation may be very expensive and/or time consuming.
  - ▫ Experimentation with the real system may entail considerable risk (such as accidents).
- The need to evaluate alternative system designs or operating policies under identical traffic conditions.

Traffic simulation models have been under development by many researchers for almost three decades. Several models have been tested with each having its advantages and disadvantages. The model which is described here (NETSIM) has been the subject of extensive testing, and its reported results have been favorable.

NETSIM Model. The Network Simulation (NETSIM) model is a microscopic, stochastic simulation model (*21*). It is an extension of the Urban Traffic Control System (UTCS-1) model which incorporated and expanded on two earlier models, DYNET and TRANS (*62*). NETSIM is designed primarily to provide the engineer with a powerful tool for analyzing and evaluating a wide range of traffic control and surveillance concepts for complex street networks.

NETSIM treats a street network as a series of interconnected directional links and nodes. Each link represents a particular approach to a node, and changes in link characteristics can be modeled by inserting mid-block nodes. A link may contain up to five lanes of traffic plus a left and a right turn pocket. Traffic generators, such as parking lots and minor streets, may be modeled as sink or source nodes. Along links, vehicles are processed in a time-scan format subject to alternative traffic controls imposed on the nodes (yield or stop sign, signal with pretimed or traffic-actuated controllers, etc.). Vehicle motion is governed by a series of car-following, queue-discharge, and lane-changing algorithms (*21, 63*).

Table 3.6. Summary of Toronto experiments

Strategy	Central Business District (CBD)	Suburb
SIGOP	Equivalent to existing	Existing better by 3.2 percent
TRANSYT	Equivalent to existing	Existing better by 2.5 percent
Combination	4.5 percent better than existing	2.8 percent better than existing
RTOP	4.8 percent better than existing	Existing better by 6.3 percent

Source: Reference (*54*)

58

Inputs to NETSIM include network geometry, traffic flow rates, saturation flow rates, turning movements and counts, traffic composition, and type of signal controller, mode of operation, and timing settings. Outputs include a variety of measures of effectiveness such as delay, stops, cycle failures (for pretimed signal controllers), fuel consumption, and emissions. NETSIM does not perform design tasks; rather it evaluates the effectiveness of different alternative designs as specified by the user's input.

NETSIM is written in FORTRAN IV for use with 32-bit computer systems. It can handle as many as 99 nodes, 160 links, and 1,600 vehicles at any instant. The model has been the subject of extensive field testing, evaluation, and validation; and it is one of the most widely used network simulation models today. NETSIM is maintained by the Federal Highway Administration.

Some enhancements to NETSIM are currently being developed including an interactive graphic capability called NETGRAF (*21*). This capability is being developed at the University of Washington. NETGRAF will enable the user to use the postprocessor function of NETSIM more effectively and will provide on-line graphical comparisons between the measures of effectiveness obtained from each NETSIM execution run. Other enhancements to NETSIM are being researched by FHWA and some have been reported by Lieberman (*64*), based on an informal user survey conducted by KLD Associates, Inc. The survey results indicated four possible enhancements: (1) easing the input preparation effort, (2) reducing the computational cost of NETSIM execution, (3) extending the output capabilities, and (4) adding more features which have been introduced by the users.

NETSIM/BPS Model. NETSIM/BPS is the basic NETSIM model modified to simulate bus preemption at intersections. This logic provides the means to advance or extend those signal phases which service an oncoming bus. Two sets of logic are provided: one set for a far-side bus stop, the other set for a near-side bus stop. The program can simulate strategies for green extension, red truncation, cycle-skipping, and the cross-street/main-street preemption selection. At the current time, the model is modified to process 20 nodes, 40 detectors, and 40 links operating in a bus-preemption environment.

The input data consist of the basic parameters of the original NETSIM program plus other parameters related to the preemption logic such as: green extension durations, red truncation durations, cycle length, detector surveillance parameters, and bus trace parameters. Program output includes measures of effectiveness normally of interest to researchers (speed, delay, etc.), estimates of fuel consumption and emissions for each vehicle type, and bus stop statistics.

The only advantage of NETSIM/BPS over the basic NETSIM program is the capability of incorporating bus preemption in the evaluation process. However, this program version lacks the ability to simulate preemption systems with either single or dual ring actuated controllers.

TRANSYT-7F. The TRANSYT-7F program contains a powerful traffic simulation model well suited for studying variable effects of network configurations, platoon cohesion, arrival/discharge patterns at the stopline, as well as fuel consumption, delay, etc.

Section Control

The concept of section control is often desirable when working with large signal networks and digital computer control. Figure 3.19 illustrates a signal network which has been divided into sections. All of the signals shown in Figure 3.19 could be under the control of one central control unit and operated as a single system. It might be desirable, however, to operate the signals as two separate sections with different timing plans (cycle length, splits, offsets) because of varying traffic conditions in the sections. For example, the signals in section 1 might be operating with a cycle length of 80 seconds, while those in Section 2 might be operating on a 60-sec cycle.

The major conditions which indicate the need and feasibility of operating a group of signals as two or more sections are:

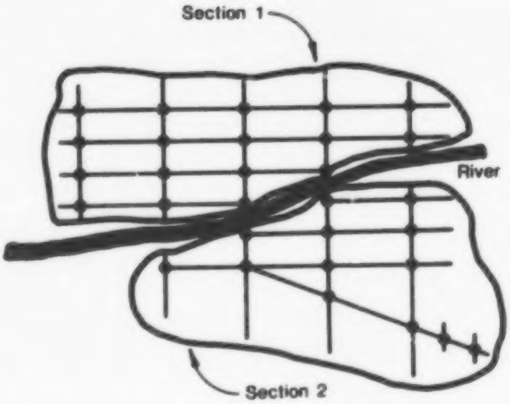


Figure 3.19. Section control configuration

59

- Different traffic conditions
- Lack of need to coordinate the signals in one section with those in another (barrier or distance separation)

Section Configuration

An important consideration in section control is the definition of the control area boundaries and the groupings of signals that will operate within these boundaries. There are three main factors which govern the section configuration. These factors are (*65, 66*):

- There should be uniformity in traffic patterns throughout the section.
- Section boundaries should be chosen in such a way that there will be minimum disruption to traffic flow at the interface between sections because of lack of coordination.

Other factors that should be considered in determining section boundaries include (*65, 66*):

- Political jurisdictions — Places where different goals and objectives may require different types of control.
- Existing communications systems — A detailed discussion of these systems is presented in Chapter 8 of this Handbook.

Computer-supervised signal control is particularly suitable in those areas where subsystem boundaries cannot be easily defined and might change with time of day. In such systems, the configuration of the different sections might be changed by modifying the data stored in the computer rather than requiring extensive modifications in data communications.

Saturated Flow Conditions

A saturated flow condition develops when the traffic demand at a point (or points) in a street network exceeds the capacity for traffic movement for a sustained period of time. This condition manifests itself at an intersection through the development of long queues which may reach from one intersection to another. When this condition occurs, traffic is unable to move even when it receives a green light, and jam conditions develop.

A different concept of control is needed to clear traffic when jam conditions develop. Two types or degrees of saturated flow can occur as follows:

- Saturated flow at a few signalized intersections in the network
- Widespread saturation in the network

Control concepts have been considered to deal with these two basic types of saturated flow.

Critical Intersection Control (CIC). If the saturated flow conditions are limited to a few critical intersections, then special control techniques can be utilized at these points in a network. The critical intersections are usually defined from past experience and provided with a greater number of detectors to permit the following:

- Detection of saturated conditions
- Detection of all approach movements
- Implementation of special control techniques

The basic concept of critical intersection control (CIC) would be as follows:

- A saturated flow condition is detected on one or more of the approaches to the critical intersection.
- The control mode at the critical intersection is changed from network mode to critical intersection mode.
- Under the critical intersection mode, the intersection operates as an isolated intersection with the objective of increasing capacity (and, therefore, decreasing congestion) on the approach or approaches with the saturated flow conditions.
- The difference between CIC and traffic-actuated control is that CIC makes adjustments to the split of all signal phases used by the timing plan. Deviations from the section cycle length are restricted.
- When the saturated condition is cleared up and this status can be detected, then the control mode can be switched back to the network mode.

In CIC, the calculation of the split for all phases requires a knowledge of traffic demand on all phases prior to the beginning of the cycle on which the adjustment is to be made. Because of the time-lag inherent in the data collection and computation process, there is a need for predicting traffic demand. Different prediction methods have been proposed. One method postulates that demand is proportional to traffic volume plus queue length at the end of red. A second method assumes that demand is proportional to a linear combination of traffic volume and occupancy. Prediction errors degrade the potential benefits of adjusting splits. Localized benefits often result at intersections where traffic fluctuations exceed two cycles in duration, but are of shorter duration than could be satisfied by timing plan changes for the entire subnetwork. CIC may not be appropriate at intersections where competing demand is highly variable but reasonably stable for two or more consecutive cycles.

It should not be implied that CIC is only applicable to saturated flow conditions. It may be desirable to utilize CIC at selected intersections with volume levels at less than saturated conditions. In this case the CIC logic may have the objective of allocating the total green time on a cycle-by-cycle basis in accordance with traffic demand on the various approaches. This type of control may reduce delays and prevent the development of serious congestion by obtaining a better allocation of green time to the various approaches of a critical intersection.

Network Saturation. When congestion becomes widespread in the network (as opposed to a few congested intersections), then the congested or critical intersection method is no longer effective. With heavy network saturation, almost all approaches become loaded, and traffic is unable to move.

The NCHRP-sponsored Project 3-18 (*2*) to develop guidelines for improving the traffic operations on oversaturated street networks. The project was undertaken by researchers at the Polytechnic Institute of New York and it resulted in the NCHRP Report 194, "Traffic Control in Oversaturated Street Networks (*67*). The guidelines described in this report were developed by means of simulation and analytical studies, field tests, and national surveys. The report enumerates several candidate treatments categorized under the following headings (*67*).

- Minimal response signal remedies-intersection
- Minimal response signal remedies-system
- Highly responsive signal control
- Enforcement and prohibition
- Turn-bays and other nonsignal remedies
- Major lane assignments
- Disruptions to the traffic

Traffic Metering. When traffic demand for movement exceeds the capacity of a signal network (as in the case of saturated-flow conditions), then delay must occur. One basic approach to a control concept for saturated network conditions would be to manage this delay in such a manner as to facilitate movement on preferential streets and to clear the saturated condition as soon as possible.

With this approach, the signal control could be utilized to store vehicles on certain links of the street network and to meter them into preferential streets which would then lead them away from the congested area. The signal timing on the preferential streets could be established to maximize flow in the desired direction.

In the case of central business districts (CBD), it might be desirable to extend the control to include the exits of parking lots or parking garages. The control system could store and meter traffic from these facilities as required by traffic conditions. The metering of traffic (ramp control) has become an accepted concept of freeway control. It seems desirable and likely to extend this concept to urban streets.

Pedestrian Control

The provision for pedestrian movement and safety is always a prime control factor at signalized intersections on arterial streets and closed networks. Since many closed networks are located in the central business district of a city, large volumes of pedestrians seeking to cross the streets at many of the signalized intersections are very common.

Pedestrians are generally permitted to cross at signalized intersections by one of the following operational options (*7*).

- With the pedestrian walk interval starting concurrently with the vehicle green interval on that phase.
- No pedestrian signal display (pedestrians cross the street with the parallel vehicular green indication).
- Exclusive pedestrians phase while all vehicular traffic is stopped.

As recommended by the MUTCD when separate pedestrian displays (WALK, DONT WALK) are used, the minimum WALK interval generally varies between 4 and 7 sec. The purpose of this interval is to allow the pedestrian ample opportunity to leave the curb before the pedestrian clearance interval commences. Several studies have indicated that the 4-sec WALK interval is usually adequate when there are fewer than 10 pedestrians per cycle (*7*).

The MUTCD mandates that a pedestrian clearance interval always be provided where pedestrian indications are used (*6*). A flashing DONT WALK indication is displayed during this interval long enough to allow the pedestrian to travel from the curb to the center of the farthest travel lane before opposing vehicles receive a green indication. Some agencies terminate the flashing DONT WALK and display a steady DONT WALK at the onset of the yellow vehicular change interval in order to encourage those pedestrians still in the crosswalk to complete the crossing without delay. In this case, the pedestrian clearance time equals the flashing DONT WALK plus the yellow change interval.

In calculating the pedestrian clearance interval, the typical walking speed of 4 fps (as cited in the MUTCD) is

61

assumed to represent the normal pedestrian. At those locations where the composition of pedestrians indicates the presence of a significant number of people crossing at speeds slower than normal (elderly, handicapped, children, and some female pedestrians), a lower walking speed may be used in calculating the pedestrian clearance time.

At intersections where there are no separate pedestrian displays, the time allocated to vehicular traffic must consider the pedestrian's reaction time to the vehicular green indication and the time to move across the street. *The Traffic Engineering Handbook* (*18*) recommends the following formula for determining the minimum vehicular green interval:

$$G = 5 + \frac{D}{4} - Y \qquad (3.28)$$

Where:

G = Minimum green interval, sec
D = Length in feet of the longest crosswalk in use during the phase (or the portion of that distance subject to vehicular conflicts)
Y = Duration of the associated yellow interval, sec

A minimum starting time of 5 sec and a walking speed of 4fps are suggested, but these may be varied as conditions might warrant.

An example of a calculation to determine minimum pedestrian timing as follows:

Assume:

$D = 80.0$ ft

$Y = 4$ sec

Walking speed = 4.0 fps

5-sec time to initiate walking

$$G = 5 + \frac{80.0}{4.0} - 4 = 21 \text{ sec}$$

Thus, the length of the green interval has to be a minimum of 21 sec for the example. If the pedestrian movements are extremely heavy, however, it may also be necessary to provide a longer green interval. Also with wide, divided roadways, it is sometimes desirable to provide crossing time sufficient to only reach the center median. A pedestrian would then cross the roadway in two signal cycles. Another alternative would be the provision of a delayed green interval to accommodate heavy pedestrian movements.

A basic operational problem regardless of phasing technique is the lack of pedestrian understanding or compliance with pedestrian indications. The clearance function of flashing DONT WALK indication is a commonly misunderstood feature. More serious for traffic signal systems is the fact that most pedestrians do not use pedestrian push buttons (*68*), thus detracting from system efficiency and safety.

3.10 AREAWIDE SYSTEM CONTROL

The three basic types of signal control (isolated, arterial, and closed network) that have been discussed are illustrated in Figure 3.20. In the past, traffic engineers have tended to view these three types of control separately, and relatively little thought was given to the concept of controlling all of the traffic signals within the limits of an urban area or political jurisdiction with a single control system.

With the introduction of digital computers and advanced communication techniques into the field of traffic control, it is now feasible — from both an economic and a technical viewpoint — to consider the surveillance and control of all traffic signals in an urban area as a total system under the supervision of a command control center. This approach to total system control has been defined as Areawide System Control (*69, 70*).

Major advantages of Areawide System Control are listed as follows:

- Total surveillance and control — A concept giving the traffic engineer continuous surveillance and control of his total signal system. Equipment failures anywhere in the system can be detected almost instantaneously, and traffic performance data can be collected from all over the street network.
- Control strategy — The development of the best possible control strategy to control isolated, arterial, or closed network signals and the uniform application of this strategy to signals all over the city.
- Equipment — Standardization and reduction in number of equipment types. Application of this total

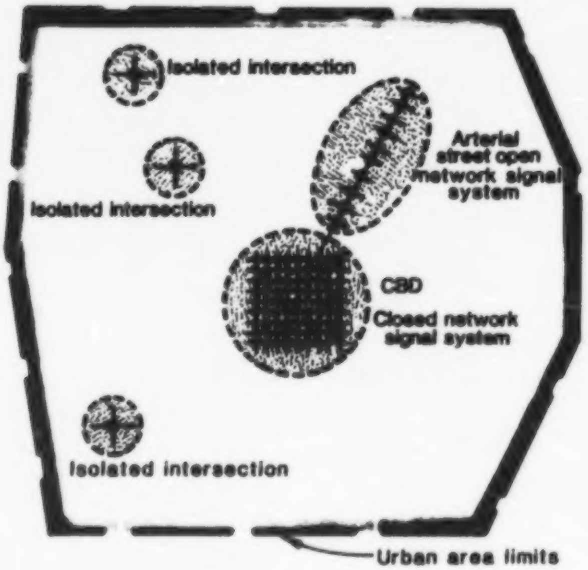


Figure 3.20. Types of signal systems

approach should produce maintenance efficiency and economy.

Control Concepts

Two basic concepts of control emerge as one considers the application of Areawide System Control. These concepts will be discussed in the following sections:

- Centralized — Concept in which all control logic and surveillance capability reside in one location.
- Decentralized, multilevel — Concept in which control logic and surveillance capability is decentralized from a geographic viewpoint and placed at various levels in a hierarchical organization of surveillance and control functions.

Centralized Control Systems. The centralized type of control system is currently the one in predominant use. It is characterized by having all of the decision-making capability (or control logic) and surveillance capability located at one geographic point and on one level. Data from all detectors in the system are fed back to a central processing unit, with all local controllers connected to a central control unit and all decisions and control commands made and dispatched from the central control unit. This concept is illustrated in Figure 3.21. Advantages of a centralized control system include the following:

- All control equipment is located in only one center.
- The system is generally less complex to develop and maintain since only one level of control logic exists. However, in system covering a broad geographic area, communication costs may negate this factor.
- Field hardware is less complex — Local controllers are simply switching units and, therefore, easier to maintain.

Special care must be exercised in the design of a centralized control system when a great number of signals that are spread over a large geographic area are to be placed under control. Special areas of concern include the following:

- Capacity — In terms of the number of real-time elements (detectors, local controllers) that must be supervised or controlled
- Communications — In terms of minimizing the cost of collecting and distributing data and commands to a network of signals and detectors
- Flexibility — In terms of control strategies and implementation capabilities

Tarnoff (*71*) provides a good discussion of these problems and techniques for handling them.

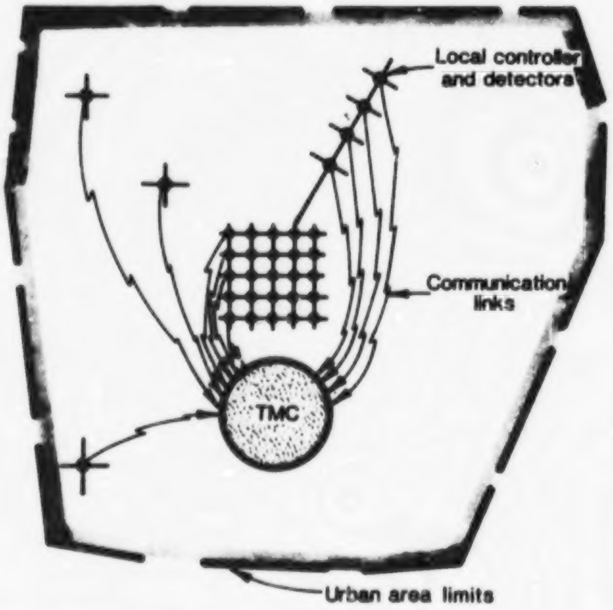


Figure 3.21. Centralized signal control system

Source: Reference (69)

Decentralized, Multilevel Control System. A graphical concept of a decentralized, multilevel control system is illustrated in Figure 3.22. The three levels of control logic and surveillance which are indicated are described as follows:

- Level 1 — Located at the intersection. Control device would have the following functions:
    - Monitoring of detectors and logical control decisions for one intersection
    - Monitoring of equipment failures (detectors, lamps, local control)
    - Collection and summary of detector data
    - Communication of data on traffic flow and equipment performance to the Level 2 controller
- Level 2 — Located in a relatively central location within its region of control. Functions of the regional controller would include the following:
    - Monitoring of traffic flow and equipment performance data from Level 1 controllers for communication to Level 3 control center
    - Supervision of Level 1 controllers. Decision-making on control mode (isolated or system), control strategy selection, and coordination of Level 1 controllers
- Level 3 — Located in a reasonably central location within the urban area. Function would be that of a command-control center. Data on any signalized intersection in the city could be monitored from this center, which would receive and process data on traffic flow conditions and support surveillance and display devices. Also, the control center would receive data on equipment failures to trigger corrective action.

Some potential advantages of a decentralized, multilevel control system would include the following (*69, 72-74*):

- Ability to reduce communication cost by preprocessing data and by concentrating data for transmission
- High level of fail-safe capability since system is not dependent upon one central control or central communications gear (failure of one part of the system without affecting other parts)
- Greater capacity to handle real-time elements (detectors, local controllers)
- Greater flexibility in control strategy
- Greater implementation flexibility

Some potential disadvantages of a decentralized, multilevel control system would include the necessity for the following:

- Maintaining more complex equipment in the field
- Developing a more complex control procedure
- Providing multiple control locations

Multijurisdictional Control Systems

Multijurisdictional control is a form of areawide traffic signal control where the control area is comprised of more than one jurisdiction, and traffic flows do not respect jurisdictional boundaries. One of the earliest multijurisdictional control systems is the one installed in Ottawa, Ontario, and Hull, Quebec, in 1974. This system is unique in terms of being bilingual and interprovincial (*75*).

Depending on the desired level of jurisdictional independence, the organizational structure of multijurisdictional control systems can be one of the following basic schemes:

- Centralized scheme without provision for jurisdictional monitoring and control — This scheme of control requires a central master computer which supervises and coordinates traffic signals in the entire urban area. Overall direction, management, and guidance would be provided by a committee comprised of representatives for all affected agencies. Coordination across jurisdictional boundaries would be performed subject to operating guidelines prescribed by the representative committee.
- Centralized scheme with provision for jurisdictional monitoring and control — Similar to the above scheme, a central master computer supervises and coordinates traffic signals in the entire urban area, but each jurisdiction would have the ability to monitor and control the intersections within its boundaries. Each jurisdiction could have a control console with a CRT, a display map for its intersections, and a line printer with access to the central computer. Coordination between jurisdictions would be possible according to a predetermined interagency agreement. Each individual jurisdiction would have the capability to set operating parameters for its intersections and could operate them as a part of the total urban system or as individual subsystems (sections) within the jurisdiction. The central master computer would require representative operational staffing from the different jurisdictions, but each jurisdiction could staff their local control center at the level they determine to be appropriate. Otherwise, the central computer would operate the signal sections within their jurisdiction according to the predetermined interagency agreement.
- Decentralized scheme — This scheme would be characterized by jurisdictional computers in addition to a central master computer. Each jurisdictional computer would control the traffic signals within its boundaries. The central master computer would supervise the areawide traffic operations and implement coordination across jurisdictional boundaries where applicable. The central computer would also supervise the communication between the jurisdictional computers.

Figure 3.23 illustrates the different options of multijurisdictional control. Part A of this figure shows the centralized scheme which provides for the lowest degree of jurisdictional independence. Part B illustrates the centralized scheme with provision for jurisdictional monitoring and control through local control centers. Part C illustrates the decentralized scheme which provides for maximum control flexibility at the jurisdictional level.

3.11 INCREMENTAL BENEFITS OF DIFFERENT LEVELS OF CONTROL

The main goal of any traffic signal control system is to improve the levels of service on the urban street network. The degree of success in meeting the goal is usually measured by the reduction in travel times, delays, and stops which directly influence vehicle operating costs, fuel consumption, vehicle emissions, and traffic safety. Given the full spectrum of signal control systems options which have been described earlier in this chapter, the purpose of this section is to provide a summary of the incremental impacts and costs of these options. Most of the material presented here is based on a report by Wagner (*76*) entitled "Energy Impact of Urban Transportation Improvements" which was prepared for the Institute of Transportation Engineers, two reports on estimating highway user costs, fuel consumption, and vehicle emissions which were prepared by FHWA (*77, 78*), and a report published by the American Association of State Highway and Transportation Officials (AASHTO) on estimating highway user benefits (*79*).

Estimating Fuel Consumption

Recent research has shown that for most urban automobile trips, fuel consumption per vehicle-mile correlates linearly with average travel time per mile (*80, 81*). This can be expressed as follows:

65

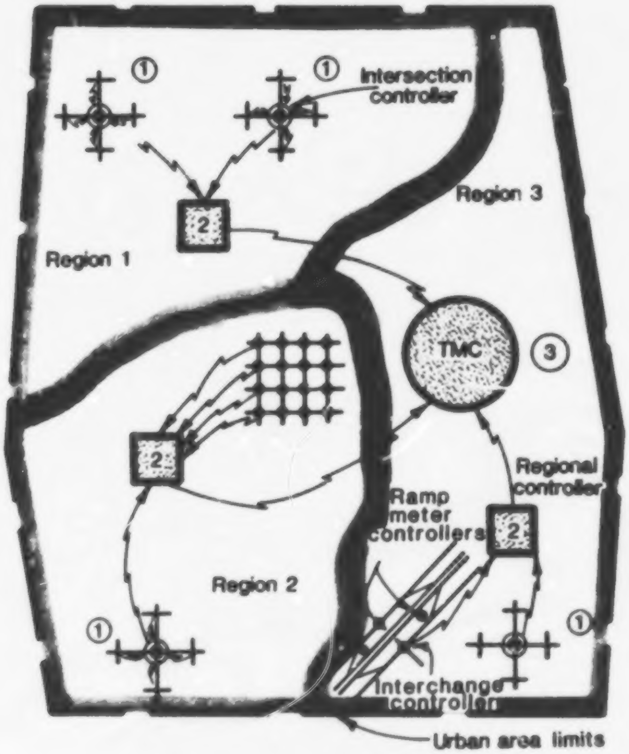


Figure 3.22. Decentralized signal control system

Source: Reference (69)

$$Ø = K_1TT + K_2D + K_3S \qquad (3.29)$$

Where:

F = Fuel consumption rate, gal per veh-mi
TT = Total travel in vmh
D = Total delay in veh-hr/hr
S = Total stops in stops per hour
K_i = Coefficients of regression, which are functions of free speed

Equation 3.29 was derived from field data collected by the General Motors Research Laboratories for average (uniform) driving speeds up to about 35 mph which is typical on most urban streets. Based on observations on the 1976 fleet of automobiles, Wagner (*82, 83*) found that the value of K1 = 0.0425 and the value of K2 = 0.01. Slightly different values for K1 and K2 were found in other studies (*80, 81*). Relationships between fuel consumption rate and average transient speed (reflecting stops and speed changes) for different types of vehicles were developed by Raus (*78*). Dale (*77*) presented a simple procedure for estimating fuel consumption rates, vehicle emissions, and highway user costs. In this procedure, the fuel consumption rate in gallons per vehicle is decomposed into three components: fuel consumption for uniform speed (Figure 3.24), fuel consumption resulting from stops and slowdowns (Figure 3.25), and fuel consumption resulting from idling (Table 3.7).

Estimating Vehicle Emissions

The major pollutants emitted by motor vehicles are carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) and lesser amounts of sulfur oxides and particulates. Currently, about 75 percent of CO, 50 to 65 percent of HC, and about 65 percent of NOx in urban areas come from motor vehicles. The health hazard of CO is that it is able to combine with hemoglobin in blood which results in the impairment of normal transfer of oxygen from the lungs to the rest of the body. Hydrocarbons and nitrogen oxides are not a direct problem by themselves, but rather they play a significant role in the formation of photochemical smog.

Raus (*78*) presented a simple method for estimating vehicle emissions based on data published by the U.S. Environmental Protection Agency. Table 3.8 provides composite emission factors of carbon monoxide, hydrocarbons, and nitrogen oxides for low altitudes (4,000 ft and below) and high altitude (above 4,000 ft). Table 3.9 gives similar factors for the State of California because its emission controls are stricter than the rest of the nation. Raus reported that the values derived by this method should not be translated directly into air quality measures or applied to pollution standards which depend on many other factors such as time, atmospheric conditions, etc.

A second method for estimating vehicle emissions has been proposed by Dale (*77*) Figure 3.24 provides emission factors for CO, HC, and NOx which are expected from 1,000 veh-mi at various uniform speeds. Table 3.7 provides estimates of emission rates due to idling.

Estimating Highway User Costs

Highway user costs are the total of vehicle operating costs, travel time, and accident costs. Vehicle operating costs can be computed using the procedures described in the "Manual on User Benefit Analysis of Highway and Bus-Transit Improvements" (*79*). Tables 3.10 and 3.11 provide estimates of operating costs due to running at uniform speeds and due to speed change cycles for passenger cars for January, 1983, conditions and price levels. To reflect changes in price levels after January, 1983, the data in Tables 3.7, 3.10, and 3.11 must be multiplied by the appropriate factor which accounts for inflation or deflation.

The excess travel time due to speed changes above continuing at a particular initial speed for passenger cars is given in Table 3.12. The monetary value of travel to road users has been explored by many researchers including Thomas and Thompson (*84*) and Stopher (*85*). The cost of accidents is not as well documented in the literature.

Impacts of Traffic Signal System Improvement

A comprehensive synthesis of traffic signal system improvement impacts was completed by Wagner (*82*) under FHWA sponsorship. These impacts were analyzed at both the project level and the areawide level. Percent improvement in overall average travel time or travel speed was used as a basis of comparison. Estimates of fuel consumption, improvement in air quality, and reduction in road user costs can be made accordingly.

Project Level Impacts. The degree of improvement in overall traffic performance which results from a given traffic signal improvement project depends, to a large extent, on the control methods used before the project implementation. The more primitive the level and quality of the base condition, the greater the potential for improvement (*76*).

Extensive survey of evaluations of traffic signal improvement projects from around the United States was conducted by Wagner (*82*). Experience with these projects was grouped into five categories representing different actions and varying base condition levels. Overall travel time or speed improvements were as follows (*76, 82*):

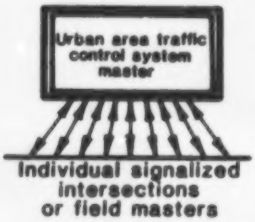
- Interconnecting previously uncoordinated signals, pretimed signals, and providing newly optimized timing plans and a central master control system resulted in 25 percent reduction in average travel time.
- Installing advanced computer control where the base condition was interconnected pretimed signals operating with old timing plans (mainly single dial) resulted in 17.5 percent reduction in average travel time, primarily due to implementation of optimized timing plans.
- Implementing advanced computer control where the base condition was non-interconnected, traffic-actuated control resulted in 16 percent reduction in average travel time.
- Installing advanced computer control where the base condition was interconnected multidial pretimed control with relatively active signal timing management resulted in eight percent reduction in average travel time.
- Optimizing traffic signal timing plans where the base condition was various forms of master control with relatively crude timing plans resulted in 12 percent reduction in travel time.

The above project evaluation results indicate that a commitment to high quality signal timing plan optimization efforts, including periodic updating of timing plans on a continuing basis, is essential in all signal systems from the primitive to the most advanced. The "set it and forget it" policy results in significant wastes of resources invested in the road and traffic control systems.

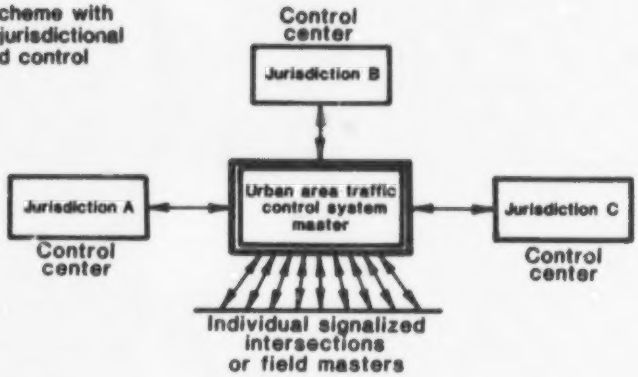
Areawide Impacts. Improving traffic signal operations, particularly on arterial streets, has powerful areawide impacts. To help illustrate, a simplified scenario for

67

(A) Centralized scheme without provision for jurisdictional monitoring and control


Urban area traffic control system master
Individual signalized intersections or field masters

(B) Centralized scheme with provision for jurisdictional monitoring and control


Control center
Jurisdiction B
Jurisdiction A
Control center
Urban area traffic control system master
Jurisdiction C
Control center
Individual signalized intersections or field masters

(C) Decentralized scheme

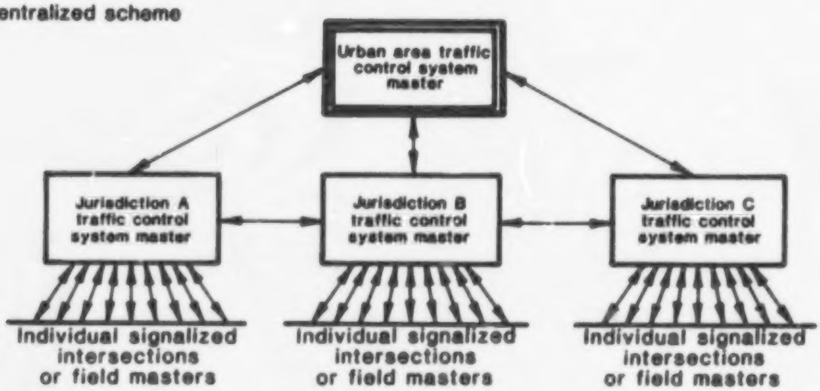

Urban area traffic control system master
Jurisdiction A traffic control system master
Jurisdiction B traffic control system master
Jurisdiction C traffic control system master
Individual signalized intersections or field masters
Individual signalized intersections or field masters
Individual signalized intersections or field masters

Figure 3.23. Schemes of multijurisdictional control

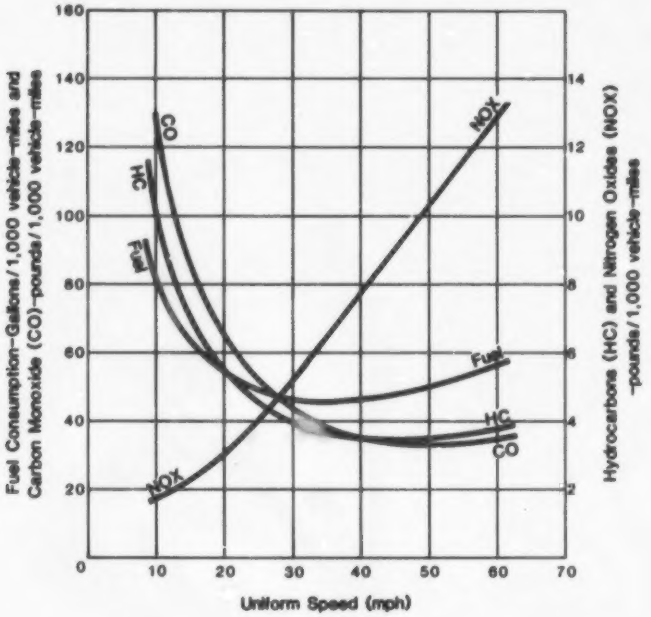


Figure 3.24. Fuel consumption and emissions of carbon monoxide, hydrocarbons, and nitrogen oxides from driving 1,000 miles at various uniform speeds (for light-duty vehicles)

implementing a comprehensive traffic signal system improvements package in a hypo thetical area of one million population was made by Wagner (*76, 82*). This scenario is summarized in Table 3.13. Reducing vehicle-hours of travel (vht) by 10 percent resulted in 3.5 percent savings in areawide motor vehicle fuel consumption, assuming that traffic signal system improvements have a negligible effect on vehicle-miles of travel (vmt). The possibility that improving the level of service due to signal system improvements will result in some degree of induced vehicular travel remains an elusive and controversial issue. Recent research on travel demand forecasting which was conducted by Cambridge Systematics (*86*) suggests that induced vmt caused by improving quality of service on existing roadways is small in the short-term and would fall far short of offsetting the energy savings and emissions reductions from improved traffic flow. The data in Table 3.14 support this conclusion. These data summarize recent predictions made by Cambridge Systematics for the Environmental Protection Agency (*86*).

Results of the simplified scenario described in Table 3.13 illustrate that signal timing plan optimization of previously coordinated signals, and the interconnection and optimization of signal timing plans at previously uncoordinated signals are responsible for the major share of overall travel time reduction and the associated energy savings.

Costs of Traffic Signal System Improvement

The annual cost range per signalized intersection of three basic traffic signal system improvements are summarized in Table 3.15 (*76*). It should be noted that precise cost estimates depend heavily on the particular requirements and characteristics of individual projects.

Cost-Effectiveness Comparisons

Traffic signal system improvements rank as one of the most cost-effective urban transportation improvement actions. The impact assessment data of the hypothetical scenario in Table 3.13, and the cost data (in 1979 dollars) in Table 3.15 were used by Wagner (*82*) for analyzing the cost-effectiveness of traffic signal system improvements. Table 3.16 presents results of cost-effectiveness analysis (*82*). The following remarks can be made:

- Traffic signal timing plan optimization is the most cost-effective element of a signal system improvement program. Its annual cost of $300 to $400 per intersection translates to only 2.1 to 2.8 cents per veh-

Table 3.7. Rates of fuel consumption and emissions and total vehicle operating costs for an idling engine

Item	Amount (Per 1,000 Veh-Hr)
Fuel[a]	650 gal of gasoline
Carbon monoxide (CO)	2,430 lb
Hydrocarbons (HO)	160 lb
Nitrogen oxides (NO_x)	50 lb
Total vehicle operating costs	$747.50

[a] January 1983 conditions and price levels

Source: Reference (77)

hr reduced. In other words, each dollar spent for signal timing optimization produces 36 to 48 veh-hr of travel time savings. In terms of energy savings, each dollar spent for signal timing optimization produces 21 to 29 gal of fuel savings.

- Interconnection and optimization of previously noninterconnected signals has a cost range of $760 to $2,700 per intersection, or 2.9 to 9 cents per vehicle-hour of travel saved by such improvements. In terms of energy savings, each project dollar buys from 7 to 24 gal of fuel savings.

- Advanced computer-based master signal control systems require an additional annual cost (over and above simple forms of master control) of about $1,100 per intersection, or 11 cents per vehicle-hour of travel saved. Each dollar invested saves approximately 9 veh-hr of travel, or about 5 gal of fuel savings.

- A comprehensive signal system improvement package such as the one outlined in Table 3.13 would cost about $1 per capita annually, or about five cents per vehicle-hour saved. Approximately 20 million vehicle-hours of travel time would be saved annually, total, or 20 vehicle-hours saved for each dollar of cost. In terms of energy savings, such a program would require an investment of 7.6 to 12.2 cents to save a gallon of fuel. Each dollar invested would return 8 to 13 gal of fuel savings.

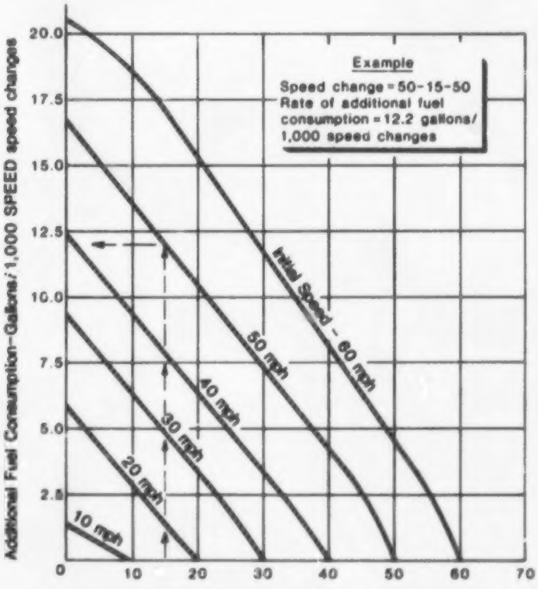


Figure 3.25. Additional fuel consumption of vehicular speed changes above consumption of continuing at uniform speed (for light-duty vehicles)

3.12 SPECIAL CONTROLS

Special controls are defined as traffic control applications other than the standard control of signalized intersections. Relative to surface street systems, the following types of special controls will be considered:

- Diamond interchange control
- Directional controls
- Priority systems
- Speed control

The control concepts associated with each of these types of special controls will be discussed in the following material.

Diamond Interchange Control

There are many variations of diamond interchanges: conventional full diamonds, half diamonds, split diamonds, and others. All varieties come with and without frontage roads. Figure 3.26 illustrates four basic types of diamond interchanges (*87*) Approximately 75 percent of all diamond interchanges are full diamonds with or without frontage roads (*88*).

Several operational problems can occur with signalization of diamond interchanges. One problem occurs when there is a spillback from one of the ramp intersections through the other intersection. When this happens, traffic at the upstream ramp intersection may be partially or completely halted, thus reducing capacity of that intersection. When both off-ramps do this simultaneously, the entire diamond interchange becomes locked-up, and no vehicles can go forward. Another spillback that can influence operation is when the left-turn pocket overflows and spills back into a through lane, thus reducing the capacity available for through traffic. A third type of spillback is off-ramp spillback. This occurs when there is a long queue of vehicles on the off-ramp and backs down onto the freeway, thus creating a dangerous situation between high-speed freeway vehicles and stopped vehicles.

Basic Phasing Schemes. Initial signal control at full diamond interchanges was provided mainly by a three-phase pretimed signal sequence as shown in Figure

Table 3.8. Composite emission factors (grams/veh-mi) for low and high altitudes

		Ambient Temperature (Fahrenheit)									
		Low Altitude[a]					High Altitude[b]				
Average Speed (Mph)	Pollutant	0	20	40	60	80	0	20	40	60	80
5	HC	24	21	19	18	17	30	26	24	22	21
	CO	339	274	234	210	195	443	351	294	260	238
	NO_x	4	4	4	4	4	3	3	3	3	3
10	HC	14	12	11	11	10	18	16	14	13	13
	CO	181	146	126	113	105	245	196	166	148	137
	NO_x	3	3	3	3	3	2	2	2	2	2
15	HC	10	9	8	8	7	13	12	11	10	10
	CO	126	102	88	79	73	177	142	121	109	101
	NO_x	3	3	3	3	3	2	2	2	2	2
20	HC	8	7	7	6	6	11	10	9	8	8
	CO	100	81	69	62	58	144	116	100	89	83
	NO_x	3	3	3	3	3	3	3	3	3	3
25	HC	7	6	6	5	5	9	8	8	7	7
	CO	84	68	58	52	48	123	99	85	76	71
	NO,4	4	4	4	4	4	3	3	3	3	3
30	HC	6	6	5	5	5	8	7	7	6	6
	CO	72	58	49	44	40	107	86	74	66	61
	NO_x	4	4	4	4	4	3	3	3	3	3
35	HC	6	5	5	4	4	7	7	6	6	6
	CO	63	50	42	38	35	94	76	65	58	54
	NO_x	4	4	4	4	4	3	3	3	3	3

[a] 4,000 ft and below
[b] Above 4,000 ft

Source: Reference (*78*)

Table 3.9. Composite emission factors (grams/veh-mi) for the State of California

Average Speed (Mph)	Pollutant	Ambient Temperature (Fahrenheit)				
		0	20	40	60	80
5	HC	21	18	17	15	15
	CO	232	204	184	169	159
	NO_x	3	3	3	3	3
10	HC	12	11	10	9	9
	CO	126	111	101	93	88
	NO_x	3	3	3	3	3
15	HC	9	8	7	7	7
	CO	89	79	71	66	62
	NO_x	3	3	3	3	3
20	HC	7	7	6	6	6
	CO	71	63	57	53	49
	NO_x	3	3	3	3	3
25	HC6	6	5	5	5	5
	CO	60	53	47	44	41
	NO_x	3	3	3	3	3
30	HC6	6	5	5	4	4
	CO	51	43	40	37	35
	NO_x	3	3	3	3	3
35	HC	5	5	4	4	4
	CO	45	39	35	32	30
	NO_x	3	3	3	3	3

Source: Reference (*78*)

Table 3.10. Automobile running cost at uniform speed on selected grades (dollars per 1,000 veh-mi)

Grade (Percent)	Uniform Speed (Mph)										
	5	10	15	20	25	30	35	40	45	50	55
Level	260.39	194.26	175.50	169.04	167.30	167.44	169.23	172.15	174.95	178.05	182.19
2[a]	242.63	185.15	173.66	167.82	165.05	164.43	166.06	168.97	172.92	176.55	181.26
4[a]	251.31	195.26	181.47	174.80	171.77	171.05	171.67	172.44	176.24	180.13	185.08
6[a]	262.49	207.55	192.80	186.20	183.33	182.16	182.50	183.72	185.61	188.93	193.59

[a] The running cost figure: Average of the running cost on the positive grade plus the running cost for the same distance on a minus grade

Note: January 1983 conditions and price levels

Source: Reference (*104*)

Table 3.11. Excess automobile running cost of speed change cycles above cost of continuing at initial speed (dollars per 1,000 speed change cycles)

Initial Speed (Mph)	Speed Reduced to and Returned from (Mph)										
	Stop	5	10	15	20	25	30	35	40	45	50
5	1.67										
10	5.12	2.36									
15	10.29	5.99	2.84								
20	15.61	10.51	6.35	2.68							
25	22.69	16.36	11.21	6.57	3.43						
30	29.25	22.27	16.52	11.40	7.42	3.89					
35	35.80	28.36	21.96	16.62	11.98	7.78	3.59				
40	42.35	34.83	28.14	22.19	17.02	12.20	7.50	3.83			
45	48.91	41.73	34.81	28.62	22.57	17.06	11.92	7.80	3.85		
50	55.47	48.44	41.61	35.12	28.23	22.37	16.64	11.86	7.62	3.87	
55	62.02	55.16	48.16	41.53	34.69	28.20	21.84	16.30	11.46	7.24	3.59

Note: January 1983 conditions and price levels

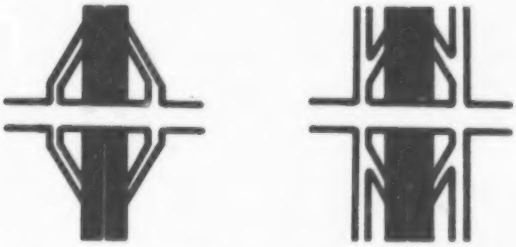
Source: Reference (*104*)

3.27, or by two non-interconnected full-actuated controllers with one controller at each intersection. As traffic volumes continued to grow, operational experience indicated that improved signalization strategies were needed to increase interchange capacity and to reduce operational problems (due to spillbacks) and delay.

The 4-phase sequence represents a major advancement in the signalization of diamond interchanges. One of the advantages of this phase sequence is that left-turning vehicles are not stored in the center of the diamond. The 4-phase, 2-overlap sequence, shown in Figures 3.28 and 3.29, was developed by the Texas Transportation Institute in the late 1950s for use with pretimed and full-actuated controllers. This phasing sequence has been very popular among traffic engineers, particularly when there is heavy ramp traffic that may be unbalanced.

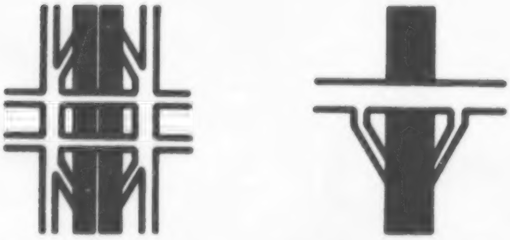
Control Modes. Depending on the need for interconnection with adjacent traffic signals, diamond interchange signals can operate according to one of the following three principal modes of control.

- Isolated signal control — In this mode, signalized intersections at the ramp terminals operate independently from adjacent signalized intersections.
- Interconnected signal control — The two signalized intersections at the ramp terminals are interconnected to improve the interchange's operational efficiency.
- Signal System Control -- In this mode, major consideration is given to providing progressive traffic movement along the frontage road and/or the crossing roadway, as shown in Figure 3.30. Each of the above modes of diamond interchange control can be implemented using one of the following types of traffic signal controllers.
- Pretimed Controllers — These controllers can be used effectively where a limited number of traffic patterns are required and then there are no significant unanticipated changes in these patterns. Interconnection and/or coordination with adjacent traffic signal controlled intersections can be easily provided. A combination of the phasings shown in Figures 3.27 and 3.28 can be implemented under pretimed control. The basic phasings can also be modified if two controllers are used (one at each cross-street intersection) through changes in the split and offset (*89*).
- Caltrans Diamond Interchange Software — The



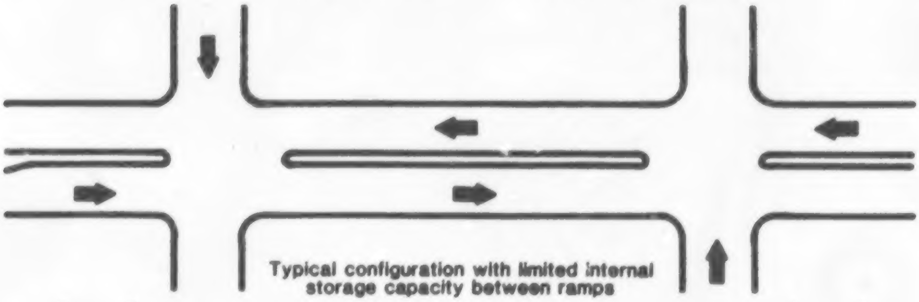
Full diamond interchange

Full diamond interchange with frontage roads

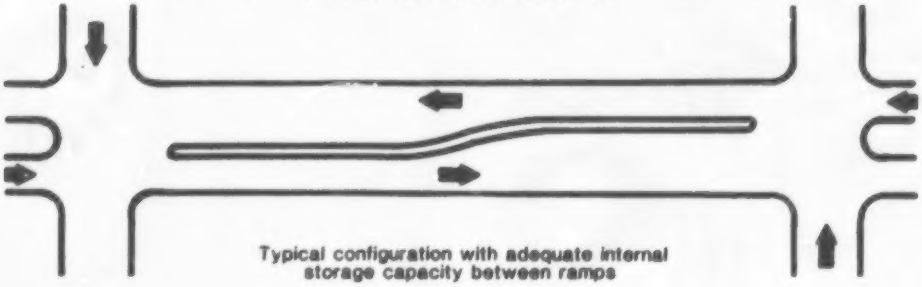


Split diamond interchange

Half diamond interchange



Typical configuration with limited internal storage capacity between ramps



Typical configuration with adequate internal storage capacity between ramps

Figure 3.26. Types of diamond interchanges

Table 3.12. Excess hours consumed for speed change cycle above continuing at initial for speed for automobiles (hours per 1,000 speed change cycles)

Initial Speed (Mph)	Speed Reduced to and Returned from (Mph)										
	Stop	5	10	15	20	25	30	35	40	45	50
5	1.02										
10	1.51	0.62									
15	2.00	1.12	0.46								
20	2.49	1.62	0.93	0.35							
25	2.98	2.11	1.40	0.80	0.28						
30	3.46	2.60	1.87	1.24	0.70	0.23					
35	3.94	3.09	2.34	1.69	1.11	0.60	0.19				
40	4.42	3.58	2.81	2.13	1.52	0.97	0.51	0.16			
45	4.90	4.06	3.28	2.57	1.93	1.34	0.83	0.42	0.13		
50	5.37	4.54	3.75	3.01	2.34	1.71	1.15	0.68	0.35	0.11	
55	5.84	5.02	4.21	3.45	2.74	2.08	1.47	0.94	0.57	0.28	0.09

Source: Reference (*104*)

California Department of Transportation has developed a software program for the Model 170 Controller unit which can provide the phase sequences shown in Figures 3.27, 3.28 and 3.29. Copies of this program are available from the FHWA (*87*) or from manufacturers of Model 170 Controller units.

- NEMA Full-Actuated Controllers — Two standard NEMA full-actuated controller units can be used to

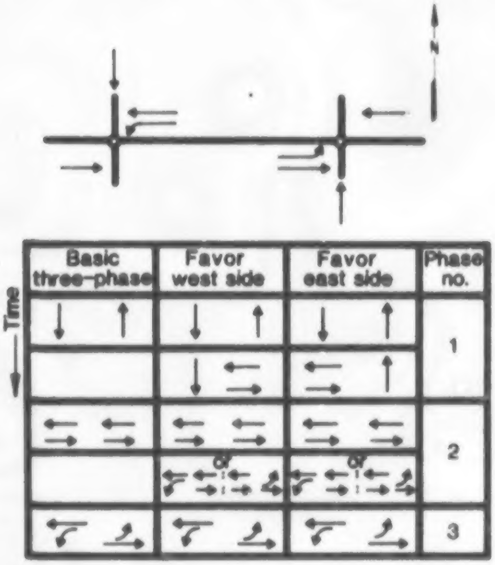

N
Basic three-phase
Favor west side
Favor east side
Phase no.
Time
1
or
2
3

Figure 3.27. Three-phase pretimed diamond interchange phasing

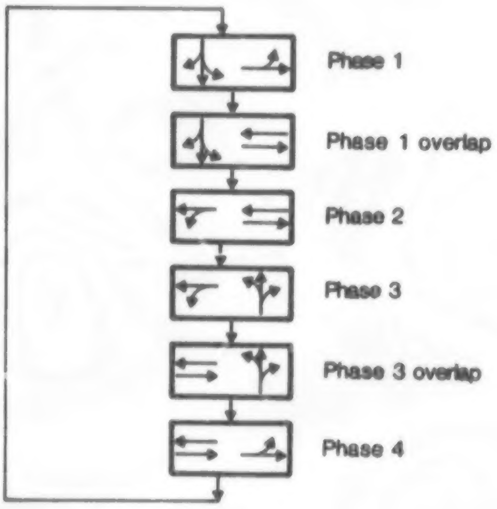

Phase 1
Phase 1 overlap
Phase 2
Phase 3
Phase 3 overlap
Phase 4

Figure 3.28. Four-phase pretimed diamond interchange phasing

Table 3.13. Travel time reduction and fuel consumption impacts of a hypothetical traffic signal system improvement for an area of one million population

Traffic Control Improvement Project	Baseline Annual Vehicle Hours of Travel Affected (Millions)	Improvement in Travel Time (Percent)	Reduction in Annual Vehicle Hours (Millions)	Reduction in Annual Fuel Consumption (Millions of Gal)	Reduction in Areawide Total Fuel Consumption (Percent)
1. Optimize signal timing at 500 previously coordinated intersections	60	12	7.2	4.3	1.3
2. Interconnect and optimize signal timing at 250 previously uncoordinated intersections	30	25	7.5	4.5	1.4
3. Install advanced computer control system at 500 intersections (same locations as in No. 1 above)	60	8	4.8	2.9	0.8
Total program	90	16 of signalized arterial vht 10 of signalized total vht	19.5	11.7	3.5

Notes: Total annual vht for area of 1 million population = 200 million veh hr. Total annual vmt for area = 5,000 million veh mi. Total annual fuel consumption for area = 332.5 million gal. Total signalized arterial system is assumed to account for 60 percent of areawide total vht or 120 million veh hr annually. Total system is assumed to have 1,000 signals.

Source: Reference (76)

provide the 3-phase operation shown in Figure 3.27 or the 4-phase operation shown in Figure 3.29

- Texas Diamond Controller — This full-actuated controller design was developed by the Texas Department of Highways and Public Transportation to provide phasing in accordance with traffic demand and interchange geometrics. One software modified 8-phase NEMA controller unit with special internal programming logic is used to provide the 4-phase operation shown in Figures 3.29 and the 3-phase operation shown in Figure 3.32. The change from one phasing operation to another can be made by time clock or by external traffic-responsive logic.

The Texas diamond controller has been incorporated into the FACTS computer control system described earlier. Under this control, the computer supervises the signal operation of each frontage road intersection providing any coordinated phase combination (shown in Figure 3.31) to provide optimum interchange operation and/or frontage road progression. When computer control is lost, the controller will automatically return to the phasing shown in Figure 3.29 or Figure 3.32 (*38*).

A detailed discussion of each of the above types of signal controllers is presented in Chapter 6.

Urban Interchange. A recent concept for the geometric design of diamond interchanges has gained acceptance in parts of the country; the concept, called "Urban Interchange" design, is shown in Figure 3.33. The design provides for: (1) efficient operation under high volume balanced flow conditions, (2) single intersection control, and (3) less traffic signal equipment requirements. Its principal disadvantages are: (1) nondirectional phasing patter, (2) large conflict area, (3) high lost times, (4) nontypical movements, and (5) high costs.

Table 3.14. Example estimates of daily areawide impacts of a comprehensive traffic control system improvement program (composed of traffic signal system interconnection, timing plan optimizations, and master control system improvements)

Areawide Characteristic	Change in Daily Areawide Level (Percent)
Vehicle miles of travel	+ 1.1
Total vehicular travel time	−11.8
Total fuel consumption	− 3.2
Total air pollutant emissions	
HC	− 5.0
CO	− 5.4
NOx	+ 6.9

Source: Reference (*82*)

PASSER-III Model. The Progressive Analysis and Signal System Evaluation Routine, Model III (PASSER-III) is a time-based optimization model. It is used for analyzing the phasing needs and determining the optimal traffic signal timings at signalized diamond interchanges (*90, 91*) Like PASSER-II (84), it was developed at the Texas Transportation Institute.

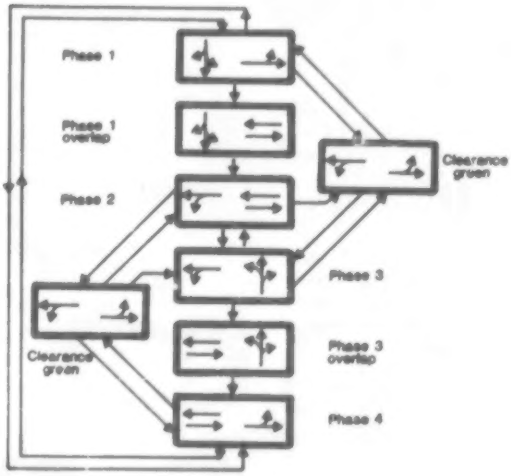


Figure 3.29. Four-phase full-actuated diamond interchange phasing

The control modes considered by PASSER-III are: (1) the isolated interchange mode (signalized diamond interchange with or without frontage roads), and (2) the progressive frontage road mode (series of interconnected interchanges with progression on the frontage roads). In the isolated interchange mode, PASSER-III can analyze five identified phasing patterns which include the four-phase, two-overlap sequence and different variations of the three-phase sequence. The model examines all possible combinations of phasing patterns and varies the offset to find the phasing pattern and offset which minimize the total delay in the interchange. In the progressive mode, the optimal cycle length is determined to maximize the progression bandwidth. Progression may be one-way or two-way (with or without preference to one direction). Both the isolated interchange mode and the progressive frontage road mode can be run together or separately to examine alternative solutions (*21*).

Although PASSER-III is designed primarily to study fixed-time and fixed-sequence control, the delay-offset analysis built in the model can be used to study various full-actuated phasings and to determine the effects of different interchange approach lane configurations, left-turn configurations, and U-turn lane provisions.

The model inputs include turning movements, saturation capacity flow rates, distances between intersections, average links speeds, queue clearance intervals, phasing

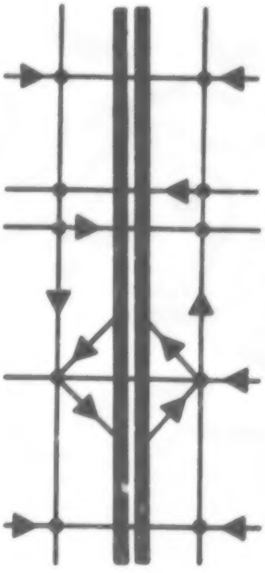


Figure 3.30. Special application frontage road progression

Table 3.15. Summary of annual costs of various traffic signal system improvements

Traffic Control Improvement	Approximate Annual Cost per Signal, 1980 (Dollars)			
	Implementation Cost per Signal (4)	Equivalent Capital Outlay[a]	Operations and Maintenance[b]	Total
Optimize previously interconnected signals	—	—	300-400	300-400
Interconnect and optimize	2,000-10,000	260-1,300	500-1,400	760-2,700
Advanced computer-based master control (including interconnection and optimization)	5,000-13,000	760-1,800	1,100-2,000	1,860-3,800
Approximate marginal cost of advanced computer-based master control	3,000	500	600	1,100

[a] Equivalent annual capital outlay is computed using 10 percent interest and 15-year life for interconnect; 10-year life for marginal costs of advanced master control.

[b] Annual operations and maintenance cost plus 10 percent of capital cost for interconnect plus 20 percent of marginal capital costs for advanced control; optimization cost is included in all cases.

Source: Reference (*82*)

Table 3.16. Cost-Effectiveness analysis of hypothetical traffic signal system improvement program for an urban area of one million

Traffic Control Improvement Project	Baseline Vehicle Hours of Travel Affected (Millions)	Reduction in Areawide Energy Consumption (Percent)	Reduction in Annual Energy Consumption (Millions of Gal)	Annual Project Cost, 1980 (Dollars)	Project Cost per Gallon Reduced (Dollars)	Gallons Reduced per Dollar of Project Cost
Optimize signal timing at 500 intersections	60	1.3	4.3	150,000 −200,000	0.035 −0.047	21−29
Interconnect and optimize signals at 250 intersections	30	1.4	4.5	190,000 −675,000	0.042 −0.15	7−24
Install advanced computer control system at 500 intersections (marginal costs and impacts)	60	0.8	2.9	550,000	0.19	5
Total program	90	3.5	11.7	890,000 1,425,000	0.076 −0.122	8−13

Source: Reference (*76*)

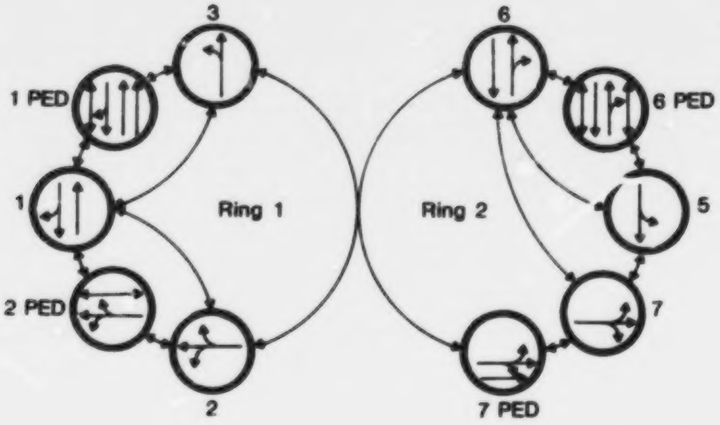


Figure 3.31. Texas diamond interchange controller phasing configuration

sequences, and minimum green times that must be provided for at each intersection.

The model output includes a data summary report, phase-interval report, optimal progression solution report, general signalization information, frontage road progression information, and time-space plots. The output varies according to the mode being analyzed. It is recommended that both modes (isolated and progressive) not be analyzed simultaneously because of the extreme computer run times (*21*).

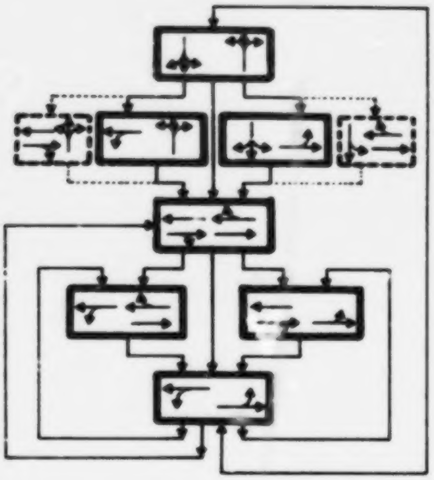


Figure 3.32 Three-phase full-actuated diamond interchange phasing

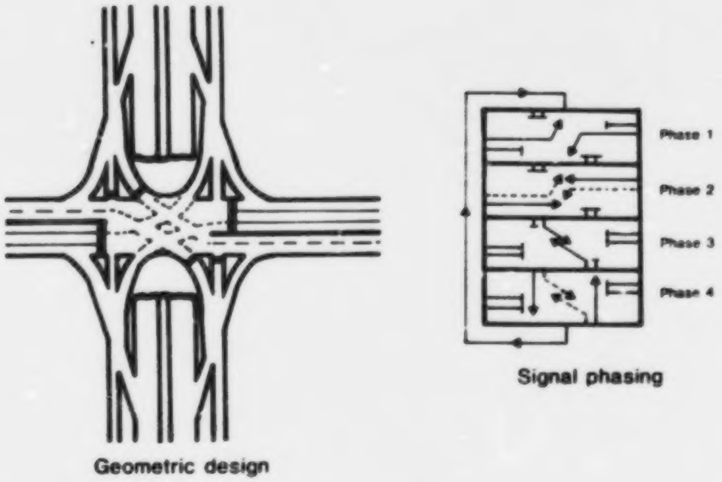
Source: Reference (*88*)

PASSER-III is written in FORTRAN IV for use with IBM 370 computers. The model has been tested extensively and is maintained by the Texas Department of Highways and Public Transportation. The interchange analysis portion was adapted in 1984 for microcomputer application.

Directional Controls

In order to make the best use of existing facilities, it sometimes becomes necessary to consider unbalanced and/or reversible-lane flow. This defines a need for special traffic controls to facilitate and control the desired movements. The two basic types of operation may be described as follows:

- Reversible Flow — Condition where a street facility may be operated as one-way inbound, one-way outbound, or two-way. Conditions warranting the use of this technique include:
  - ▫ Heavy imbalance of directional traffic flow for relatively short periods such as occur in moving traffic volumes in and out of central business districts
  - ▫ No alternate solutions such as one-way pair or street widening
  - ▫ Severe congestion and need to increase directional capacity
  - ▫ Nearby parallel street capable of handling minor directional flow during peak one-way operation



Geometric design

Signal phasing

Urban interchange

Figure 3.33 Florida urban interchange design and signal phasing

- Off-center lane movement — Partial reversal of traffic flow where traffic flow in only one or two lanes is reversed. Conditions warranting this type of operation are similar to the more drastic case of reversible flow.

The current traffic control techniques for controlling directional movement utilize signs or a combination of signs and lane-control signals. The change of operational mode is usually on a time-of-day basis. The use of separate control equipment is prevalent, but future techniques likely would combine this control function with other central control functions. Dynamic or traffic-responsive techniques for change of mode might also become more widely used in the future.

Priority Systems

Conditions may develop which indicate the need for a special assignment of the right-of-way at a signalized intersection. Thus it is necessary to consider the establishment of priority systems in the overall concept of traffic control.

High-Occupancy Vehicle Priority. A concept which is receiving increasing emphasis is that of assigning priority to high-occupancy vehicles. Such vehicles include buses, vans, and regular automobiles with multiple occupancy (carpool). The basic objective here is one of giving priority to person movement as opposed to vehicle movement.

The average occupancy of an automobile is approximately 1.2 persons per vehicle, while high-occupancy vehicles (bus, van, etc.) may have 10 to 30 times this occupancy. Thus, if priority is given to the movement of persons at signalized intersections, high-occupancy vehicles would usually be assigned the priority over regular automobiles.

Many techniques such as exclusive bus lanes are being utilized to give priority to transit movement. The primary technique to be considered in this discussion is the ability to assign transit priorities at signalized intersections. TRANSYT-7F has been used to derive optimal signal timing for providing preferential offsets for buses.

A desired objective of intersection control with bus priority becomes one of minimizing the person delay as opposed to vehicular delay. To accomplish this form of control effectively, the following are needed:

- Ability to detect the presence of a bus at an intersection approach
- Technique to estimate the movement demand in terms of number of persons for each approach of an intersection. One possible technique would be to assume an occupancy rate for automobiles and buses
- Control strategy which would minimize person delay. Such a strategy would thus give priority to buses when they were carrying large passenger loads

Research work (*92*) on bus priority systems has been conducted in the UTCS Project in Washington, D.C. This project has developed a bus detector system. Through the use of this special system, buses can be detected as they arrive on the upstream approaches of the instrumented intersections.

The original control strategy provided green interval extensions be granted for:

- Through bus — Nonstopping bus which arrives one second before the start of yellow
- Stop Bus — Stopping bus which arrives one second — plus its average loading time — before the start of yellow

During normal operation, an extension of the green interval is granted which is based on a comparison of the gain in passenger-minutes on one phase with that on an opposing phase. All eligible buses in the bus zones, as well as vehicles, are taken into account. An extension is granted to a green interval only if it has a possible net gain which exceeds a pre-established threshold. An extension of the major phase is followed by an equivalent shortening of the minor phase green interval without shortening the major phase green interval which does not affect cycle length or offset. An extension of the minor phase, however, lengthens the cycle and delays the major phase offset. The lengthened cycle is followed by a cycle which is shortened by the amount of the previous cycle extension.

A revised algorithm later provided the ability for a bus to preempt a traffic signal subject only to a consideration of limits of green times and oversaturation. The original algorithm, as indicated, was designed to minimize total passenger delay.

A report by Tarnoff (*93*) discussing the UTCS/BPS indicated the following conclusions relative to the findings of the Bus Priority System tests:

- Bus Priority System (BPS) will work satisfactorily in an urban street network. Reductions in bus travel time in excess of ten percent have been experienced in such systems.
- All signalized intersections along the urban bus route being controlled should be included in the system.
- The system must have the capability for detecting overall traffic volumes and inhibiting the Bus Priority System (BPS) operation when these volumes become excessive. If this is not done, the intersection becomes saturated with resulting delays to all vehicles, including buses.
- The Bus Priority System (BPS) concept is feasible only where bus volumes on a given route are less than approximately 30 to 50 buses per hour. Volumes in excess of this range would tend to preempt the signal at almost every cycle, which is equivalent to retiming the signal.
- Bus Priority System (BPS) operation tended to increase vehicle minutes of delay for other than instrumented buses by a value of 5 to 15 percent, depending upon bus volumes and the degree of traffic congestion at the BPS intersection.

Preemption Systems. In addition to high-occupancy vehicles, there are special cases where preemption of traffic signals may be required. Two basic cases are as follows:

- Where a signalized intersection is adjacent to a railroad track.
- Where it is desired to preempt a signal to permit the assignment of the right-of-way to firefighting equipment or other emergency-type vehicles.

In the case of the railroad preemption, detectors can be utilized to detect the approach of a train and to trigger a control reaction such as all red, flashing red, etc., which will last until the train has cleared the intersection.

Preemption for emergency vehicles is more difficult to achieve because of the problems of detecting the emergency vehicle. Some basic types of emergency vehicle systems are briefly discussed as follows:

- Vehicle-detection system — A vehicle-detection system works on an individual intersection basis and depends upon an ability to detect individual emergency vehicles.

  When an emergency vehicle is detected, using a modulated light or radar, approaching an intersection, a special signal control procedure is called into use at the affected intersection which assigns the right-of-way to the emergency vehicle. After a predetermined time period, the signal returns to normal operation.
- Green-band system — The green-band system provides for a green indication to be displayed on all intersections along a selected route which is to be traveled by an emergency vehicle. The routes are predetermined, and the right-of-way assignment along a route is made by throwing a switch at a central location (such as a central fire station). The signals are then switched back to normal operation after the reported passage of the emergency vehicle(s) — usually a prespecified time.
- Flashing-signal system — A flashing-signal system works exactly the same as the green-band system,

with the exception that the signals along a selected route are put in a flashing mode. The emergency vehicles then proceed along a route with a flashing yellow. The flashing system is designed to reduce delay by allowing some vehicles to proceed through the flashing red indications with caution.

The basic problem associated with the consideration of preemption systems is to define what applications should be accommodated within the signal system design. The benefits of providing certain special controls must be weighed against the adverse effects they may create relative to the total flow of traffic.

Television Surveillance

Closed circuit television (CCTV), though in limited use, is an important element of modern traffic surveillance and control systems. It enables operators in a central control room to view traffic conditions at locations where cameras are placed. The nature and time of occurrence of traffic incidents (accidents, stalled vehicles, debris on the road, parking violation, etc.), the type of response required, and the effect on the upstream network can be determined quickly, so that suitable action can be taken. The primary disadvantage is procurement and maintenance costs.

Although the major applications of CCTV in the United States have been in freeway surveillance and control projects, CCTV has been recently included as part of traffic control installations for urban streets in such cities as Columbus, Ohio (*94*), and Overland Park, Kansas (*95*). In Japan, CCTV has been extensively utilized in urban street traffic surveillance and control systems (*96*). Similar systems are also used in Europe for intersection observation purposes (*97, 98*). In these systems, CCTV cameras are usually placed at critical intersections in the street network. Monitors for CCTV in the urban street control center in Columbus, Ohio, are shown in Figure 3.34. A detailed discussion of CCTV applications in traffic surveillance and control is presented in Chapter 4.

3.13 MEASURES OF EFFECTIVENESS

Any new traffic control system or modification to an existing system is intended to satisfy a goal or a set of goals. The goal may have been started explicitly, such as: "reduce congestion in the core area of a city by minimizing stops and delays," or it may have been implied by a pledge such as "increase accessibility to dying downtown businesses." Goals are easy to state, but they may be impossible to measure. Therefore, measures of effectiveness (MOE's) are used to provide a quantitative basis for determining the capability of traffic control systems and their strategies to attain the desired goals. To successfully determine goal attainment, the MOE's must be related to the goals. Also, if there are no comparative analyses, the measures must be identified with base values to determine goodness or badness of goal attainment. Other desirable criteria for selecting MOE's include simplicity within the constraints of required precision and accuracy, sensitivity to relatively small changes in the nature of implementation of a control strategy, and measurability on a quantitative scale within reasonable time, cost, and manpower budgets.

Measures of effectiveness which are commonly computed from electronic surveillance data of traffic performance include the following:

- Total travel time
- Total travel
- Number and percentage of stops
- Delay
- Total minute-miles of congestion

These measures of effectiveness are used to indicate the improvement in efficiency of traffic flow resulting from control. The basic methods used to determine these measures of effectiveness are described briefly in the following sections.

Total Travel Time

One primary measure of effectiveness used to evaluate freeway and urban street control systems and strategies is total travel time. Expressed in units of vehicle-hours, it represents the product of the total number of vehicles using the roadway during a given time period times the average travel time of the vehicles.

The average travel time, ttj, in hr, of vehicles over a roadway section j is:

$$tt_j = \frac{X_j}{\overline{U}_j} \tag{3.30}$$

Where:

X_j = Length of roadway section j, in mi and
$\overline{U}_j$ = Average speed of vehicles over roadway section j, in mph

Total travel time, TTTj, in veh-hr, over section j is:

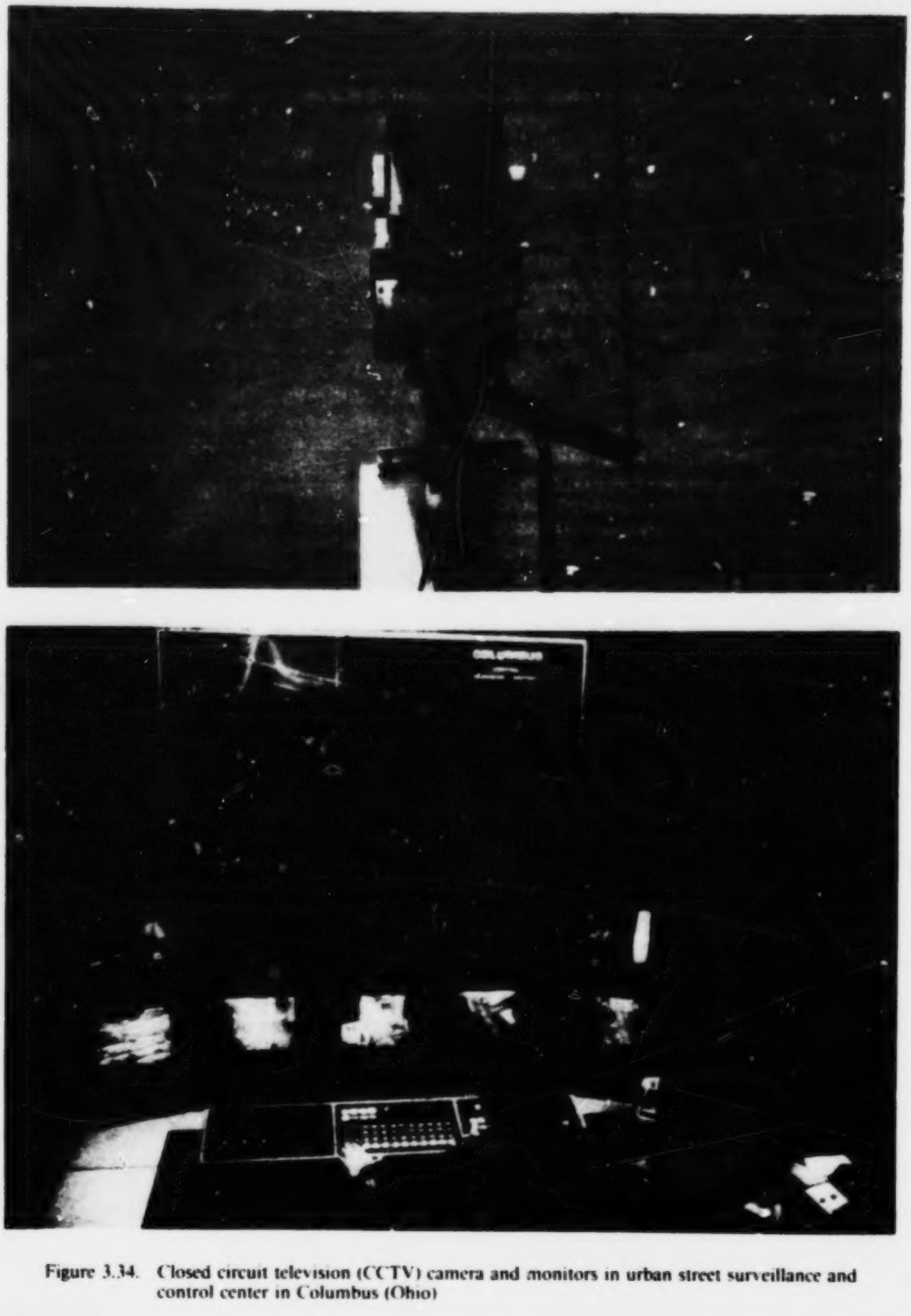


Figure 3.34. Closed circuit television (CCTV) camera and monitors in urban street surveillance and control center in Columbus (Ohio)

Source: Reference (94)

$$TTT_j = N_j\, tt_j = \frac{N_j X_j}{\bar{U}_j} \qquad (3.31)$$

Where:

N_j = Number of vehicles traveling over section j, during time period, T
tt_j = Average travel time of vehicles over roadway section j, in hr

If the expression for $\bar{U}$s from Equation 3.10 is substituted into Equation 3.31, total travel time, TTT_j, in veh-hr, is determined by:

$$TTT_j = \frac{5{,}280\ T X_j O_j}{100 d_j} \qquad (3.32)$$

Where:

T = Specified time period, in hr
O_j = Occupancy in section for time period T, in percent
d_j = Effective vehicle-detector length in section j, in ft

Total travel time, TTT, in veh-hr, for all sections of a roadway is:

$$TTT = \sum_{j=1}^{K} TTT_j \qquad (3.33)$$

Where:

TTT_j = Total travel time for section j, in veh-hr
K = Number of roadway sections

Total Travel

Total travel is another common measure of effectiveness which is used to evaluate traffic operations. Expressed in units of vehicle-miles, it represents the product of the total number of vehicles using the roadway during a given time period times the average trip length of the vehicles.

The total travel, TT_j, in veh-mi, over a roadway section j is:

$$TT_j = X_j N_j \qquad (3.34)$$

Where:

X_j = Length of roadway section j, in miles
N_j = Number of vehicles traveling over section j during time period, T

If the expression for Nj from Equation 3.1 is substituted into Equation 3.34, the TT_j, in veh-mi, is determined by:

$$TT_j = X_j Q_j T \qquad (3.35)$$

Where:

Q = Traffic volume n section j during time period, T, in vph
T = Specified time period, in hr

Also, an inspection of Equations 3.31 and 3.34 suggests that the total travel, TT_j, in veh-mi, over a roadway section j can be derived from total travel time and average speed for section j, as follows:

$$TT_j = TT_j \bar{V}_j \qquad (3.36)$$

Where:

TTT_j = Total travel time for section j during time period, T, in veh-hr, and
V_j = Average speed of vehicles over section j during time period, T, in mph

Total travel, TT, in veh-mi, for all sections of a roadway is:

$$TT = \sum_{j=1}^{K} TT_j \qquad (3.37)$$

Where:

K = Number of roadway sections

Number and Percentage of Stops

A measure of effectiveness used to evaluate the quality of flow on urban streets is the number of vehicle stops. The calculation of the number of stops on an approach to an intersection is determined by the relationship between detector actuations and signal timing. A typical time-space diagram for number of stops computations is presented in Figure 3.35. The number of stops per cycle is the number of detector actuations which occur between T_{gc} and T_{rc}, with T_{gc} being the last time that a vehicle can cross the detector during the green interval and still clear the intersection without being stopped. The values for T_{gc} and T_{rc} are established on the basis of predetermined vehicle trajectories between the detector and the intersection. In some algorithms for computing number of stops, these trajectories remain the same for all vehicles, while in others they are varied according to the number of vehicles already determined to be stopped between the detector and the intersection. The percent of vehicles stopping can be easily computed by categorizing vehicles as either stopping or not stopping.

Delay

Without a doubt, delay expressed in one form or another is the most widely used MOE in traffic control. On urban arterials, delay is defined as the increase in travel time which is beyond that normally expected. It can be determined for a given roadway section with known length from total travel time which reflects the overall conditions, and an expected normal speed (a speed below which travel at that time of day would be considered to be delayed). Using this normal speed, a normal, total travel time can be computed by using Equations 3.31 and 3.33. This normal, total travel time, is then subtracted from the measured total travel time for the same time period to obtain delay.

In the case of urban street intersections, delay is commonly defined as the time lost at the intersection by those vehicles that are stopped. Figure 3.35 can be used to describe the computation of stopped-vehicle delay. Assuming all stopped vehicles clear the intersection on the next green, the delay, Di, in seconds, for the ith stopped vehicle is determined by:

$$D_i = R - (t_{ci} - T_r) + (t_{di} - T_g) \qquad (3.38)$$

Where:

R = Length of the red interval, in sec

T_r = Time at which the red interval begins, in sec

tc_i = Predicted time at which the ith vehicle would have reached the intersection if it had not been stopped, in sec

T_g = Time at which the next green interval begins, in sec

td_i = Predicted time at which the ith vehicle clears the intersection, in sec

Time, tc_i, is determined from the time, ta_i, at which the ith vehicle actuates the detector and a predetermined approach trajectory. Time, td_i, is determined from time, T_g, at which the next green interval begins and a predetermined departure trajectory. Some algorithms used to compute stopped-vehicle delay provide for varying the predetermined approach and departure trajectories according to the number of vehicles already stopped. Assuming all stopped vehicles clear the intersection on the next green, total stopped-vehicle delay, D, in seconds, for a cycle is determined by:

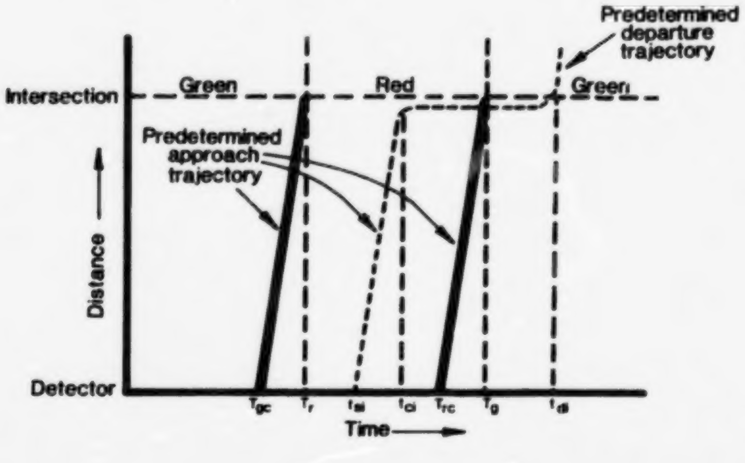


Figure 3.35 Time-space diagram for stop and delay computations for urban street control

$$D = \sum_{i=1}^{n} D_i \qquad (3.39)$$

Where:

D_i = The delay of the ith vehicle stopped during the cycle, in sec
n = The number of vehicles stopped during the cycle

An analysis of the relationship between percent stopping and approach delay, which was part of a specialized research study (99) resulted in the relationship shown in Figure 3.36.

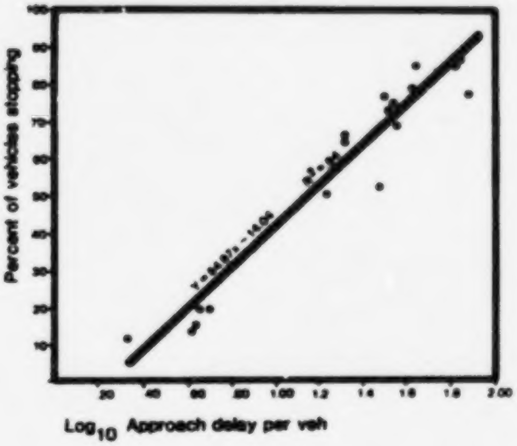


Figure 3.36. Relationship of percentage of vehicles stopping and approach delay

Source: Reference (99)

Total Minute-Miles of Congestion

One measure of effectiveness developed by the Chicago Area Expressway Surveillance Project (*100*) to evaluate freeway operations can be termed total minute-miles of congestion. This measure is intended to indicate the extent of freeway congestion in both time and space.

To compute the total minute-miles of congestion, each mainline detector is assigned a section of freeway which covers half of the distance between the adjacent mainline detector on either side. The minute-miles of congestion at each detector would be equal to the product of the minutes of congestion at the detector, times the distance, in miles, assigned to the detector. The sum of the minute-miles of congestion of all detectors then would represent the total minute-miles of congestion.

The calculation of this measure of effectiveness requires a quantitative definition of congestion. In the Chicago study, congestion was defined as a 5-min lane occupancy of 30 percent or more.

Analysis has shown that the value for total minute-miles of congestion correlates with that for total travel time. However, it is much more readily obtainable, primarily because its value is less sensitive to detector accuracy.

Several other important MOE's can be derived from those described above. Gasoline consumption and emissions, for example, can be computed from total travel time, stops, and delay (*101*).

A report by Cooper, et al. (*102*), provided much of the base work for MOE's for subsequent research work. A recently completed study on quality of flow on urban arterials provides an update of MOE's related to urban traffic control. Further research has been conducted for the Federal Highway Administration, including the study by JHK & Associates and Peat, Marwick, Mitchell & Co. entitled "Measures of Effectiveness for Multimodal Urban Traffic Management" (*101*), and the study by PRC Voorhees entitled "Quality of Flow on Urban Arterials" (*103*). The results of the PRC Voorhees study recommended the use of a single MOE, average speed, for analyzing the quality of flow on urban arterials with the stipulations that the type of arterial (particularly its cruise speed) be taken into account.

REFERENCES

1. Kurkjian, A. *Dynamic Detection and Identification of Incidents on Freeways. Vol. II: Approaches to Incident Detection Using Presence Detectors.* (Undated information brochure.) U.S. Department of Transportation, Washington, DC, Final Report No. DOT-OS-60137, 1977. (Also available from the MIT Electronic Systems Laboratory, Cambridge, Massachusetts, as Report No. ESL-R1765.)

2. Mikhalkin, B. "The Estimation of Roadway Behavior Using Occupancy Detectors." Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, California, 1970. (Doctoral Dissertation.)

3. Wardrop, J. C. "Some Theoretical Aspects of Road Traffic Research." *Proceedings of the Institute of Civil Engineers.* Part II, No. 2, 1952, pp. 325-362.

4. Breiman, L. "Space Time Relationships in One-Way Traffic Flow." *Transportation Research*, Vol. 3, 1969, pp. 365-376.

5. Gershwin, S. B. *On the Relationship Between Vehicle Flow, Vehicle Density, and Velocity Distribution.* MIT Electronic Systems Laboratory, Cambridge, Massachusetts, Technical Memorandum No. ESL-TM-570, 1974.

6. Federal Highway Administration. *Manual of Uniform Traffic Control Devices for Streets and Highways.* U.S. Department of Transportation, Washington, D.C., 1978.

7. Kell, J. H., and I. J. Fullerton. *Manual of Traffic Signal Design.* Institute of Transportation Engineers, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1982.

8. Fullerton, I. J., and J. H. Kell. *Traffic Control Devices Handbook.* JHK & Associates (in press).

9. Tarnoff, P. J., and P. S. Parsonson. *Selecting Traffic Signal Control at Individual Intersections.* National Cooperative Highway Research Program Report 233, Transportation Research Board, Washington, D.C., 1981.

10. Greenshields, B. D., et al. *Traffic Performance at Urban Street Intersection.* Technical Report No. 1, Yale Bureau of Highway Traffic, New Haven, Connecticut, 1947.

11. Webster, F. V. *Traffic Signal Settings.* Road Research Paper No. 39, Department G, Scientific and Industrial Research, H.M. Stationery Office, London, 1958.

12. Gerlough, D. L., and F. A. Wagner. *Improved Criteria for Traffic Signals at Individual Intersections.* National Cooperative Highway Research Program Report No. 32, Transportation Research Board, Washington, D.C., 1967.

13. Alsop, R. E. "Sensitivity of Delay at a Fixed-Time Traffic Signal to Small Errors in the Observations Used for Calculating the Signal Settings." *Traffic Flow and Transportation.* Chapter 17, Elsevier Publishing Company, New York, New York, 1972.

14. Pinnell, Charles. "The Value of Signal Phase Overlap in Signalized Intersection Capacity," *Traffic Engineering*, Vol. 33, No. 12, 1962, pp. 17-20.

15. Drew, Donald R. "Design and Signalization of High-Type Facilities." *Traffic Engineering*, Vol. 33, No. 7, 1963, pp. 17-25.

16. Transportation Research Board. "Interim Materials on Highway Capacity." *Transportation Research Circular No. 212*, Washington, D.C., 1980.

17. *Highway Capacity Manual.* Highway Research Board Special Report No. 87, Highway Research Board, Washington, D.C., 1965.

18. Homburger, W. S.; L. E. Keefer; and W. R. McGrath (editors). *Transportation and Traffic Engineering Handbook*, 2nd Edition. Institute of Transportation Engineers, Washington, D.C., 1982.

19. Pignataro, Louis J. *Traffic Engineering Theory and Practice.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973.

20. Gibson, David R. P. "Available Computer Models for Traffic Operations Analysis." *Transportation Research Special Report 194*, Transportation Research Board, Washington, D.C., 1982, pp. 12-22.

21. Byrne, A. S., et al. *Handbook of Computer Models for Traffic Operations Analysis.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1982.

22. Courage, K. G., and M. R. Landmann. *Signal Operations Analysis Package: Vol. 1: Computational Methodology. Vol. 2: User's Manual. Vol. 3: Programmer's Manual. Vol. 4: Portable Calculator Routines.* University of Florida, Transportation Research Center, FHWA Implementation Package 79-9, 1979.

23. Rioux, T. W., and C. E. Lee. "TEXAS — A Microscopic Traffic Simulation Package for Isolated Intersections." Presented at the 56th Annual Meeting of the Transportation Research Board. Washington, D.C., 1977.

24. Hillier, J. A. "Glasgow's Experiment in Area Traffic Control." *Traffic Engineering and Control*. Vol. 7, No. 8, 1965, and Appendix in Vol. 7, No. 9, 1966, pp. 569-571.

25. Yardeni, L. A. "Vehicular Traffic Control: A Time-Space Design." *Institute of Traffic Engineers Proceedings*. Washington, D.C., 1964, pp. 59-74.

26. Brooks, W. D. *Designing Arterial Progressions Using a Digital Computer*. IBM Corporation. (Undated.)

27. Chamberlain, R. N. *Traffic Progression Program*. IBM Corporation. (Undated.)

28. Bleyl, R. L. "A Practical Computer Program for Designing Traffic Signal System Timing Plans" *Highway Research Record 211*. Highway Research Board, Washington, D.C., 1967, pp. 19-33.

29. Little, J. D. C.; B. V. Martin; and J. T. Morgan. *Synchronizing Traffic Signals for Maximum Bandwith*. MIT Department of Civil Engineering Report No. R64-08, Massachusetts Institute of Technology, 1964.

30. Messer, C. J., et al. "A Variable-Sequence Multiphase Progression Optimization Program." *Highway Research Record 445*. Highway Research Board, Washington, D.C., 1973.

31. Wallace, C. E., and K. G. Courage. "Arterial Progression — New Design Approach." *Transportation Research Record 881*. Transportation Research Board, Washington, D.C., 1982, pp. 53-59.

32. Wagner, F. A.; D. L. Gerlough; and F. C. Barnes. *Improved Criteria for Traffic Signal Systems on Urban Arterials*. National Cooperative Highway Research Program Report 73. Transportation Research Board, Washington, D.C., 1969.

33. Lieberman, E. B., and J. L. Woo. *SIGOP-II: A New Computer Program to Calculate Optimal Signal Timing Patterns*. KLD Associates, Inc., Huntington Station, New York, New York, 1976.

34. Robertson, D. I. *TRANSYT: A Traffic Network Study Tool*. Road Research Laboratory Report No. RL-253, Grothorne, Berkshire, England, 1969.

35. Little, J. D. C.; M. D. Kelson; and N.H. Gartner. "MAXBAND: A Program for Setting Signals on Arteries and Triangular Networks." *Transportation Research Record 795*. Transportation Research Board, Washington, D.C., 1981, pp. 40-46.

36. Little, J. D. C. "The Synchronization of Traffic Signals By Mixed-Integer Linear Programming." *Operations Research*, Vol. 14, 1966, pp. 568-594.

37. Courage, K. G., et al. *Arterial Analysis Package User's Manual*. Transportation Research Center, University of Florida, Gainesville, 1981.

38. Haenel, H. E., and J. Williams. "Texas Stand Alone Arterial System." Presented at the 60th Annual Meeting of the Transportation Research Board, Washington, D.C., 1981.

39. Wallace, C. E., et al. *TRANSYT-7F User's Manual*. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1981.

40. Traffic Research Corporation. *SIGOP: Traffic Signal Optimization Program*. U.S. Bureau of Public Roads, Washington, D.C., 1966.

41. Lieberman, E. B., and J. L. Woo. *SIGOP-III User's Manual*. U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-IP-82-A, Washington, D.C., 1982.

42. Schoene, G. W.; G. W. Euler; and C. E. Wallace. "Energy Conservation Through Traffic Signal Timing Optimization." *International Conference on Road Traffic Signalling*. Institute of Electrical Engineers, London, England, 1982, pp. 49-52.

43. Federal Highway Administration. *The Urban Traffic Control System in Washington, D.C.* U.S. Department of Transportation, Washington, D.C., (Undated information brochure.)

44. MacGowan, J., and I. J. Fullerton. "Development and Testing of Advanced Control Strategies in the Urban Traffic Control System." (Three Articles.) *Public Roads*, Vol. 43 (Nos. #2, 3, 4), 1979-1980.

45. Sanderson, L. B. "UTCS First Generation Control — What's New." *Computer Control Systems Applications Group Newsletter*. Institute of Transportation Engineers, Washington, D.C., Vol. 1, No. 1, 1978, pp. 5-11.

46. Honeywell, Inc., Traffic Management Center. *UTCS Functional Description — Enhanced First Generation Software*. Federal Highway Administration, U.S. Department of Transportation, Report No. FHWA-TS-79-228, Washington D.C., 1979.

47. PetryKanyn, J. P. "Enhanced First Generation Software to Undergo Testing." *Computer Control Systems Applications Group Newsletter*. Institute of

Transportation Engineers, Washington, D.C., Vol. 2, No. 2, 1979, p. 9.

48. Yagoda, H. N., et al. "Online Forecast: Making First Generation UTCS Easier to Use." *Computer Control Systems Applications Group Newsletter.* Institute of Transportation Engineers, Washington D.C., Vol. 4, No. 2, 1982, pp. 1-3.

49. Yagoda, H. N., et al. "FORCAST On-Line: Making UTCS Easier to Use." International Conference on Road Traffic Signalling, Institute of Electrical Engineers, London, England, 1982, pp. 97-102.

50. Hunt, P. B., et al. "The SCOOT On-Line Traffic Signal Optimization Technique." International Conference on Road Traffic Signalling, Institute of Electrical Engineers, London, England, 1982, pp. 59-62. (See also *Traffic Engineering and Control*, Vol. 32, No. 4, April 1982, pp. 190-192.)

51. Bretherton, R. D., and G. I. Rai. "The Use of SCOOT in Low Flow Conditions." *Traffic Engineering and Control*, Vol. 23, No. 12, December 1982, pp. 574-576.

52. Hunt, P. B. et al. *SCOOT — A Traffic Responsive Method of Coordinating Signals.* Transport and Road Research Laboratory Report No. LR-1014, Grothorne, Berkshire, England, 1981.

53. Henry, R. D.; R. A. Ferlis; and J. L. Kay. *Evaluation of UTCS Control Strategies — Executive Summary.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report No. FHWA-RD-76-149, 1976.

54. Corporation of Metropolitan Toronto. *Improved Operation of Urban Transportation Systems.* Vol. 1 (March 1974), Vol. 2 (November 1975), Vol. 3 (November 1976), Toronto, Canada.

55. Robertson, D. I. "Traffic Models and Optimum Strategies: A Review." *Proceedings of the International Symposium on Traffic Control Systems*, Berkeley, California, August 1979, pp. 262-288.

56. Tarnoff, P. J. "Concepts and Strategies — Urban Street Systems." *Proceedings of the International Symposium on Traffic Control Systems*, Berkeley, California, August 1979, pp. 1-12.

57. Gartner, N. H. "Prescription for Demand-Responsive Urban Traffic Control." *Transportation Research Record 881*, Transportation Research Board, Washington, D.C., 1982, pp. 73-76.

58. Miller, A. J. "A Computer Control System for Traffic Networks." *Proceedings of the Second International Symposium on the Theory of Traffic Flow*, London, England, 1963.

59. Sims, A. G. "The Sydney Coordinated Adaptive Traffic System." *Proceedings of the Engineering Foundation Conference on Research Directions in Computer Control of Urban Traffic Systems.* American Society of Civil Engineers, New York, N.Y., 1979, pp. 12-27.

60. Gartner, N. H. "Demand-Responsive Decentralized Urban Traffic Control." Presented at the 62nd Annual Meeting of the Transportation Research Board, Washington, D.C., 1983.

61. Gerlough, D. L., and M. J. Huber. "Traffic Flow Theory." *Transportation Research Board Special Report 165.* Transportation Research Board, Washington, D.C., 1975.

62. Peat, Marwick, Mitchell, and Co., and KLD Associates, Inc. *Network Flow Simulation for Urban Traffic Control System — Phase II: UTCS-1 Network Simulation Model.* U.S. Department of Transportation, Federal Highway Administration, 1973. (Final Report.)

63. KLD and Associates. *Network Flow Simulation for Urban Traffic Control System — Phase II: Volume I: Technical Report.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1977.

64. Lieberman, E. C. "Enhanced NETSIM Program." *Transportation Research Board Special Report 194*, Transportation Research Board, Washington, D.C., 1981, pp. 32-35.

65. PRC Voorhees. *Computer Controlled Traffic Signal Systems.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., Implementation Package FHWA-IP-82-21, December 1982.

66. Stockfisch, Charles R. "Guidelines for Computer Signal System Selection in Urban Areas." *Traffic Engineering*, Vol. 43, No. 3, 1972, pp. 30-63.

67. Pignatara, L. J., et al. "Traffic Control in Oversaturated Street Networks." *National Cooperative Highway Research Program Report 194*, Transportation Research Board, Washington, D.C., 1978.

68. Zegeer, C. V., et al. "The Effect of Pedestrian Signals and Signal Timing on Pedestrian Accidents." *Transportation Research Record 847*, Transportation Research Board, Washington, D.C., 1982, pp. 62-72.

69. Pinnell, C.; J. J. DeShazo, Jr.; and R. L. Wilshire. "Areawide Traffic Control Systems." *Traffic Engineering*, Vol. 45, No. 4, 1975, pp. 16-21.

70. Pinnell, C., and R. L. Wilshire. "Areawide Multilevel Traffic Control Systems." *Proceedings of the Third Symposium on Traffic Control and Transportation Systems.* 1976, pp. 339-348.

71. Tarnoff, Philip J. "Distribution of Data Processing Capabilities in an Urban Traffic Control System." *Traffic Engineering.* Vol. 44, No. 11, 1974, pp. 9-15.

72. Sandell, Jr., N. R., et al. "Survey of Decentralized Control Methods for Large Scale Systems." *IEEE Transactions on Automatic Control.* Vol. AC-23, No. 2, 1978, pp. 108-128.

73. Chu, Kai-Ching. "Decentralized Controls in Real-Time Traffic Systems." *Proceedings of the 1976 IEEE Conference on Decision and Control including the 15th Symposium on Adaptive Processes.* IEEE Control Systems Society, December 1976, pp. 1030-1033.

74. Lord, J. C., and K. S. P. Kumar. "A Multilevel Distributed System Concept for Computerized Traffic Control Applications." *Proceedings of the 1976 IEEE Conference on Decision and Control including the 15th Symposium on Adaptive Processes.* IEEE Control Systems Society, December 1976, pp. 1034-1037.

75. Whitehead, Douglas. "Computerized Traffic Signal Control in Canada." *Computer Control Systems Application Group Newsletter.* Institute of Transportation Engineers, Washington, D.C., Vol. 3, No. 1, 1980, p. 5.

76. Wagner, Frederick A. *Energy Impacts of Urban Transportation Improvements.* Institute of Transportation Engineers, Washington, D.C., 1980.

77. Dale, Charles W. *Procedure for Estimating Highway User Costs, Fuel Consumption and Air Pollution.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1981.

78. Raus, Juri. *A Method for Estimating Fuel Consumption and Vehicle Emissions on Urban Arterials and Networks.* Office of Research and Development, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1981.

79. American Association of State Highway and Transportation Officials. *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements.* AASHTO, Washington, D.C., 1977.

80. Chang, M., et al. "Gasoline Consumption in Urban Traffic." *Transportation Research Record 599.* Transportation Research Board, Washington, D.C., 1976, pp. 25-30.

81. Evans L., and R. Herman. "Automobile Fuel Economy on Fixed Urban Driving Schedule." *Transportation Science.* Vol. 12, No. 2, 1978, pp. 137-152.

82. Wagner, Frederick A. *Traffic Control System Improvements: Impacts and Costs.* Report No. FHWA-PL-80-005, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1980.

83. Wagner, Frederick A. *Urban Transportation Energy Conservation, Analysis of Traffic Engineering Actions.* Final Report, Vol IV, U.S. Department of Energy, Washington, D.C., 1978.

84. Thomas, T. C., and G. I. Thompson. *The Value of Time Saved by Trip Purpose.* Stanford Research Institute, Menlo Park, California, October 1970.

85. Stopher, Peter R. "Application of Value of Travel Time To Economic Evaluation of Transport Investment Alternatives." *Transportation Research Record 587.* Transportation Research Board, Washington, D.C., 1976, pp. 19-23.

86. Cambridge Systematics, Inc, *Sketch Planning Methods for Short-Range Transportation and Air Quality Planning, Vol. II — Case Studies.* Environmental Protection Agency, Washington, D.C., 1980.

87. Federal Highway Administration. *Diamond Interchange Program — Users Manual.* Office of Research and Development, Implementation Division, Report No. FHWA-IP80-4, Washington, D.C., December 1980.

88. Munjal, P. K. "An Analysis of Diamond Interchanges." *Highway Research Record 349,* Highway Research Board, Washington, D.C., 1971, pp. 47-64.

89. Federal Highway Administration. *Signal Control Strategies for Signalized Diamond Interchanges.* Report No. FHWA-IP-80-5, Office of Research and Development — Implementation Division, Washington, D.C., December, 1980.

90. Messer, C. J.; D. B. Fambro; and J. M. Turner. *Analysis of Diamond Interchange Operation and Development of a Frontage Road Level of Service Evaluation Program — PASSER III.* Texas Transportation Institute Report No. 178-2F, August 1978. (Final Report.)

91. Fambro, D. B., et al. *A Report on the User's Manual for Diamond Interchange Signalization — PASSER III.* Texas Transportation Institute Report No. TTI-2-18-76-178-1, August 1977.

90

92. Sperry Systems Management. *Urban Traffic Control and Bus Priority — Volume I: Design and Installation.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., Report No. FHWA-RD-73-9, November, 1972.

93. Tarnoff, Philip J. "The Results of FHWA Urban Traffic Control Research: An Interim Report," *Traffic Engineering*, Vol. 45, No. 4, 1975, pp. 27-35.

94. Division of Traffic Engineering and Parking. *Traffic Control System Specifications.* Columbus, Ohio. (Undated.)

95. Schlaefli, J. L.; D. P. Masher; and R. C. Sandys. *Overland Park Traffic Control System (OPTCS) Specification.* Stanford Research Institute, Menlo Park, California, 1973.

96. Matsushita Communication Industrial Co., Ltd. *Outline of Traffic Control System: Automatic Traffic Information System and Centralized Traffic Signal Control System, Kanagawa Prefectural Police Headquarters.* Yokohama, Japan, March 1970.

97. Tillotson, Howard T. "Traffic Signal Control Using Television." *Traffic Engineering and Control*, Vol. 9, No. 9, 1968, pp. 245-249.

98. "T.V. Eye Keeps Munich on the Move." *Traffic Engineering*, Vol. 31, January 1961, pp. 15-22. (Reprint from the *Lamp*, Standard Oil Company, N.J.)

99. Reilly, W. R., et al. *A Technique for Measurement of Delay at Intersections, Vol. 1.* Report No. FHWA-RD-76-135, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., November 1976.

100. McDermott, J. M.; S. J. Kolenko; and R. J. Wojcik. *Chicago Area Expressway Surveillance and Control: An Interim Report.* Department of Transportation, State of Illinois, June 1973.

101. Kay, Jack L. "Measures of Effectiveness." *Proceedings of the International Symposium on Traffic Control Systems.* Berkeley, California, August 1979.

102. Cooper, D. L., et al. *Systems Analysis Methodology in Urban Traffic Control Systems, Final Report.* TRW Systems Group, Houston, Texas, June 1969.

103. Schoppert, D., et al. *Quality of Flow in Urban Arterials — Phase I, Vol. I.* Report No. FHWA-RD-78-199, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., December 1978.

104. Winfrey, Robley. *Economic Analysis for Highways.* International Textbook Company, Scranton, Pennsylvania, 1969.

4. Control Concepts — Freeways

CONTENTS

Section — *Page*

- **4.1 INTRODUCTION** 4.3
  - **Purpose and Scope** 4.3
  - **Congestion — A Daily Occurrence** 4.3
  - **Congestion — Its Measurement** 4.4
  - **Congestion — Its Causes** 4.4
    - ***Geometric Design Factors*** 4.4
    - ***Traffic Operations Factors*** 4.5
    - ***Random Factors*** 4.6
- **4.2 ENTRANCE RAMP CONTROL** 4.7
  - **Closure** 4.9
    - ***Application*** 4.9
    - ***Methods*** 4.10
  - **Ramp Metering** 4.10
    - ***Metering Rates*** 4.10
  - **Pretimed Metering** 4.11
    - ***System Components*** 4.11
    - ***System Operation*** 4.12
    - ***System Evaluation*** 4.14
  - **Traffic-Responsive Metering** 4.15
    - ***Fundamental Traffic Flow Relationships*** 4.16
    - ***Basic Strategy*** 4.16
    - ***Demand-Capacity Control*** 4.18
    - ***Occupancy Control*** 4.18
    - ***System Components*** 4.18
    - ***System Operation*** 4.19
    - ***System Evaluation*** 4.21
  - **Gap-Acceptance Merge Control** 4.21
    - ***Basic Concepts*** 4.21
    - ***System Components*** 4.22
    - ***System Operation*** 4.23
    - ***System Evaluation*** 4.24
  - **Integrated Ramp Control** 4.25
    - ***Integrated Pretimed Metering*** 4.25
      - *Linear Programming Formulation* 4.27
      - *Practical Considerations* 4.29
    - ***Integrated Traffic-Responsive Metering*** 4.29
    - ***Integrated Gap-Acceptance Merge Control*** 4.31
    - ***Integrated vs. Independent Ramp Control*** 4.31
    - ***Controller Interconnection*** 4.31
  - **Incremental Benefits of Different Levels of Control** 4.31
- **4.3 EXIT RAMP CONTROL** 4.33

Section *Page*

4.4 MAINLINE CONTROL 4.33
Driver Information Systems 4.34
Variable-Speed Control 4.34
Lane Closure 4.35
Warning of Lane Blockage 4.35
Improvement of Entrance Ramp Merging Operations 4.35
Traffic Diversion 4.35
Tunnel Control 4.35
Mainline Metering 4.36
Reversible Lane Control 4.38

4.5 CORRIDOR CONTROL AND SURVEILLANCE 4.39
Objective 4.39
Strategy 4.41
Incident Management 4.41
Detection 4.42
Electronic Surveillance 4.42
Closed-Circuit Television 4.44
Aerial Surveillance 4.44
Emergency Call Boxes and Emergency Telephones 4.45
Cooperative Motorist-Aid Systems 4.45
Citizen-Band (CB) Radio 4.45
Police and Service Patrols 4.46
Incident Response 4.47
Incident Removal 4.47
Television Surveillance 4.49
Cameras 4.50
Monitors 4.50
Peripheral Devices 4.50
Transmission Systems 4.50

4.6 AVAILABLE COMPUTER SOFTWARE 4.50
Model History 4.51
CORQ-CORCON Model 4.51
FREQ Model Family 4.53
INTRAS 4.53
MACK Family 4.54
SCOT Model 4.54
Online Models 4.56
DIVERT Model 4.56
STAR Model 4.56

4.7 HIGH-OCCUPANCY VEHICLE PRIORITY CONTROL 4.56
Separated Facilities 4.56
Reserved Freeway Lanes 4.58
Metered Ramp Bypass 4.61
Exclusive Ramps 4.61
Guidelines for Implementation 4.61

REFERENCES 4.64

94

4. CONTROL CONCEPTS — FREEWAYS

4.1 INTRODUCTION

Traffic control is the regulation, warning, and guidance of traffic for the purpose of improving the safety and efficiency of moving people and goods. Implementing this control process involves the installation, operation, and maintenance of various traffic control devices such as signs and signals.

Freeway management represents an expanded concept which includes freeway traffic control supplemented by such freeway operations activities as incident management, aid to stranded motorists, and driver information messages. These activities also provide for improved operation and safety during off-peak as well as peak periods for incident control and during maintenance activities by controlling traffic under varying conditions. This expanded view is reflected both in this chapter title and in the material presented.

Purpose and Scope

Freeways were originally conceived and designed as free-flowing, limited-access facilities with little advance consideration given to the possibility of needing traffic control systems. Continued growth in traffic demand and the resultant congestion have forced a search for solutions. Among those solutions evolving from research and practical experimentation, freeway surveillance and control systems, along with freeway management concepts, have become accepted as cost-effective tools for improving traffic operations on freeways.

Freeway congestion is the primary problem being addressed by freeway traffic control. For this reason, congestion — its measurement and causes — is described first in this chapter. Then, specific control concepts are described for which operational experience exists. These, which include ramp control, mainline control, and corridor control, present the following concepts:

- Restricted entry (closure, metering)
- Advisory information (speed, travel time, route guidance, diversion)
- Priority treatment (HOV operation)
- Surveillance
- Incident management (detection and response)

The discussion of each concept includes a description of:

- Control principle and parameters
- Functional components
- Experience

Congestion — A Daily Occurrence

Congestion will occur on a freeway when demand exceeds capacity. A section of a freeway where traffic demand exceeds freeway capacity is called a bottleneck. A bottleneck or congestion of this type occurs as a result of conditions which either have increased demand to a level greater than capacity, or have decreased capacity to a level less than demand.

Such congestion is a daily occurrence on many portions of freeway networks in urban areas. Even casual observation can define specific points at which congestion can be expected. Congestion routinely expected at predictable locations during specific periods of time is termed recurrent congestion. In contrast, other forms of congestion result from random or less predictable events. Such nonrecurrent congestion results most frequently from accidents and incidents. Congestion from special situations (sporting events, weekend travel, maintenance and construction activities) may be considered as nonrecurrent congestion. However, maintenance and construction activities, if not properly planned, may result in recurrent congestion. In defining strategies to deal with the problems of congestion, some perspective of the relative magnitude of each type is needed. Table 4.1 summarizes the percentages of types of congestion which were reported by Caltrans (*1*) for the Los Angeles area.

Regardless of whether congestion is recurrent or nonrecurrent, it is exhibited in terms of slow travel speeds, erratic speeds characterized by stop-and-go movement, increased and inconsistent travel times, increased accident potential, inefficient operation, and other undesirable conditions which cause user dissatisfaction. If users know to expect a certain level of congestion during peak periods, they can plan their trips accordingly. However, nonrecurrent congestion may severely impact an otherwise satisfactory trip during peak or off-peak periods. Inability to provide a reliable, even though sometimes lower, level of service is perhaps the more serious problem.

Table 4.1. Types of congestion by percentage for Los Angeles (California)

Type of Congestion		Percentage
Recurrent		43
Nonrecurrent		
Incidents	47	
Weekends	6	
Holiday weekends	3	
Others (e.g., special events)	1	
Total (nonrecurrent)		57
Total		100

Source: Reference (*1*)

Congestion — Its Measurement

A motorist usually thinks of congestion in terms of overcrowded freeways, stop-and-go driving conditions, and the frustration and discomfort of restricted maneuverability. The traffic engineer, on the other hand, often expresses congestion in terms of traffic variables such as flow rate, density (or occupancy), and average space speed, together with the fundamental relationships among them. For example, Figure 4.1 illustrates the fundamental relationship between flow rate and density. As traffic density increases from zero to some value, k_1, traffic flow rate increases, and the resulting operation is defined as noncongested. As density increases from k_1 to k_2, however, though flow rate tends to increase, traffic operations become unstable, and the probability of serious breakdown increases. Further increases in density above k_2 result in a decrease in flow rate until, theoretically, it reaches zero at jam density, k_j. The traffic flow regimes occurring at densities greater than k_2 are classified as congested.

The specific value of density used to define congestion depends on such factors as the geometrics of the freeway section, traffic composition, and weather conditions. Biggs and Mislen (*2*) have used values on the order of 50 vehicles per mile per lane, usually corresponding to a space mean speed of 35 to 50 mph and a flow rate of 1,400 to 1,800 vph per lane. McDermott (*3*) has reported that lane occupancies, in the ranges of 0 to 20 percent, 20 to 30 percent, and 30 to 100 percent indicate noncongested, unstable (impending congestion), and congested operations, respectively. Figure 4.2 shows generalized freeway traffic-operations curves which relate lane occupancy to flow rate and average space speed (*3*). As lane occupancy exceeds 20 percent, speeds decrease because of fewer and shorter gaps between vehicles, increased difficulty of lane changing, and generally more restrictive flow conditions.

Congestion — Its Causes

Much has been written about the numerous factors which contribute to the problem of congestion and its many manifestations. Of the several studies that have been performed to investigate ways to improve freeway operations, the works of Moskowitz (*4*) and Keese, Pinnell, McCasland (*5*) are representative. Later works (*6-8*) have provided theoretical explanations of freeway traffic flow describing free flow, unstable flow, and forced flow. All of the factors identified and described can be considered within the categories of:

- Geometric design factors
- Traffic operations factors
- Random factors

Geometric Design Factors. The capacity of a freeway is not constant along the entire freeway length. Certain physical features result in capacity restrictions at the location where they occur. Upstream and downstream from this location, capacity is usually slightly higher, resulting in bottleneck conditions. Today's design standards make it possible to avoid in the construction phase many such bottleneck causes. Examples of physical features which contribute to capacity reductions, and thereby congestion, include the following:

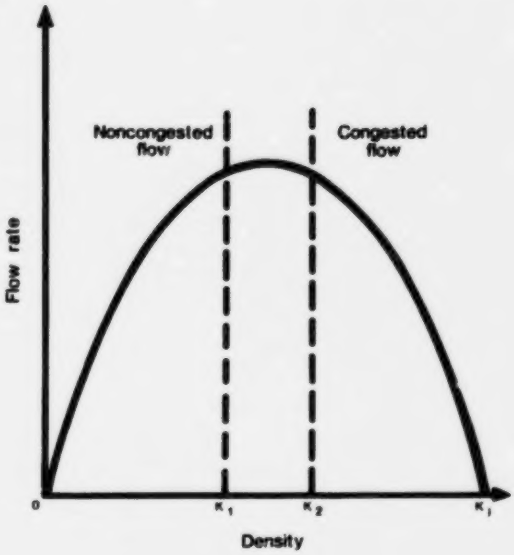


Figure 4.1. Congestion and the fundamental relationship between flow rate and density

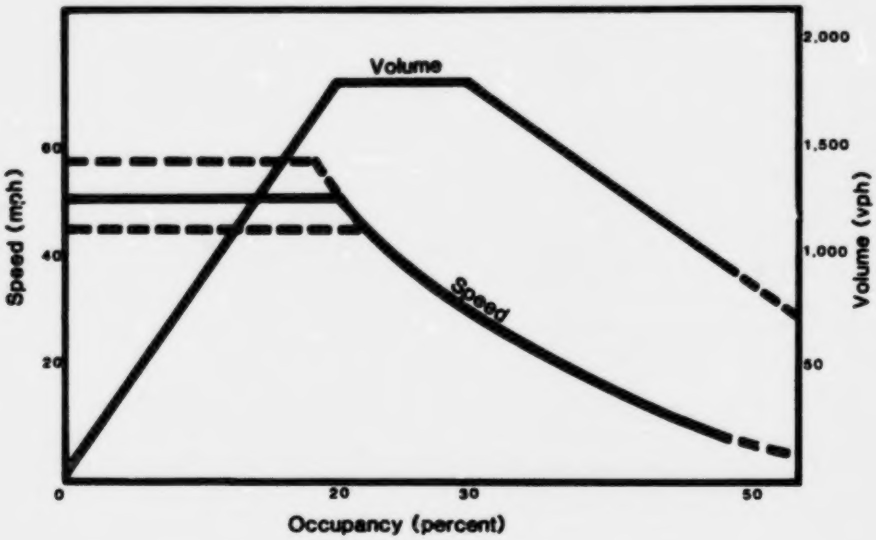


Figure 4.2. Generalized traffic flow relationships

Source: Reference (*3*)

- Reduction in lanes — Congestion may occur at locations where the number of freeway lanes is reduced. Even though the lane drop may occur at an exit ramp, the through volume may exceed the remaining capacity, thus resulting in congestion. Too, the act of weaving out of the dropped lane may create turbulence, causing speed to decrease with a resultant decrease in throughput. This may be a particular problem where multiple freeways merge without maintaining the same number of through lanes.
- Horizontal curvature — Capacity may be reduced by a moderately sharp horizontal curve. Under conditions of heavy flow, a vehicle may cross into the next lane, causing hesitation and speed decreases in adjacent lanes. Even momentary speed decreases during periods of unstable flow can result in congestion.
- Vertical alignment — The effects of steep grades have been well documented (*9*), particularly their effects on trucks. Today's design standards impose limitations on acceptable grades. Even so, vertical alignment may cause small, but imperceptible, speed changes which can affect following traffic and also result in congestion. Upgrades in tunnels, for example, are the limiting point of tunnel system capacity.
- Other physical features — Lane widths, lateral clearance, ramp design, and surface conditions can all affect freeway capacity individually and, in turn, contribute to congestion. Traffic lanes on interstate freeways are generally 12-ft wide (*10*), but older freeways may have lanes more restricted. Likewise, lateral obstructions, in the form of bridge abutments, retaining walls, illumination poles, sign supports, etc., may reduce capacity if located closer than 6 ft to a traveled lane. For example, lack of full-shoulder-width bridges has been reported to result in a point reduction of capacity on some freeways.
- Number of lanes — The number of freeway lanes is also a significant factor. The 6- and 8-lane freeways show greater average capacities per lane than do the 4-lane freeways. Table 2.1 of the *TRB Interim Materials on Highway Capacity* (*11*) shows the effect of number of lanes on freeway capacity, or maximum service volumes.

Traffic Operations Factors. Traffic operations factors which can contribute to congestion include the following:

- Volume/capacity relationship — Congestion can be expected as a direct result of the nature of supply and demand. Freeways with too much traffic attempting to use the capacity of the facility will experience congestion. Supply of traffic has already been discussed in terms of capacity. Also, a number of freeway traffic studies have observed that capacity is not uniform along a freeway section, even though the number of lanes may be constant.

97

The demand placed on a facility can be defined simply as the number of vehicles seeking to use the facility. However, measuring the flow on a freeway in an attempt to determine demand is often futile. In this case, the parameter measured is manifest demand. Frequently, a considerable volume of latent demand has been diverted to other time periods, other routes, or other modes because of present conditions. Thus, a substantial difference between actual demand and manifest demand may exist. The actual demand is best measured by origin-destination surveys where the times of the desired trips can be obtained.

The relationship of capacity and demand at a specific bottleneck is shown in the top portion of Figure 4.3. There, the demand exceeded capacity for a 30-min period. In the lower portion of the figure, congestion is shown to begin at the point of time where capacity was first exceeded, and then to extend for a time long enough to allow the capacity to dissipate the backlog of demand. Thus, the congestion period is longer than the time period for which the demand exceeds capacity.

As previously indicated, capacity is a constant property of a roadway section, while its ability to service traffic (service rate) varies over short time periods. When a section is operating at capacity (i.e., $k = k_1$) as shown in Figure 4.4, then all is well. If the incoming volume exceeds capacity, then vehicles accumulate in that section, increasing the density to, perhaps, $k = k_2$. But at $k = k_2$, the service rate is below capacity, and this decrease in service rate is the major factor causing congestion. This relationship explains why a relatively small excess demand over capacity can produce prolonged, serious congestion.

Another effect, hysteresis, which has been described by Treiterer (*12*), acts to inhibit the return of traffic flow to uncongested conditions.

- Unrestrained ramp access — Freeway bottlenecks and the attendant congestion are frequently the result of unrestrained ramp access. In such situations, ramp traffic, when added to the volume of traffic already on the freeway, will create a demand in excess of the capacity. This condition is further complicated by the frictions generated by the ramp-traffic merging maneuver.

- Exit ramp queues — Freeway mainline congestion is occasionally the result of exit ramp queues. Where the exit ramp demand exceeds the ability to process traffic through a merging area or an intersection downstream of the ramp, or where there is a lack of storage on the ramp itself, the end result is a queue of vehicles extending back onto the freeway. Such conditions can develop not only because of congestion on the surface street system, but also as a result of heavy exit ramp demand occasioned by special activities such as sporting events.

- Weaving maneuvers — The presence of heavy weaving movements frequently causes freeway mainline congestion. Heavy weaving may result from relative ramp location as determined during design and from the development of heavy traffic flows to or from specific generators.

Random Factors. Events classified as random are often easily dismissed as rare occurrences not worthy of attention. As used here, however, the term "random" refers to the inability to predict such events in terms of time and location. Examples of random events include traffic accidents, incidents, and other unpredictable situations which cause nonrecurrent congestion. Experience has shown that such random events do occur with alarming frequency. For example, it has been observed that, within a metropolitan freeway network, at least one lane could be expected to be closed or blocked for 7.2 percent of the time as a result of accidents; for 6.7 percent of the time because of vehicle stalls or breakdowns; and for 27.8 percent of the time because of maintenance operations; for a total of 41.7 percent of the time (*13*).

When a random event causes the blockage of one or more freeway lanes, the magnitude of the capacity reduction is usually disproportionate to the actual physical reduction in roadway width. For example, as indicated in Table 4.2, work on the 6-lane Gulf Freeway in Houston (*14*) reported capacity reductions from about 50 percent to 79 percent because of lane blockages. Of significance is the reduction in capacity because of the presence on the shoulder of vehicles that had been involved in an accident. Under similar conditions of lane blockage in Detroit, capacity was reduced by 42.9 percent when one of three freeway lanes was blocked (*13*).

As has been noted already, maintenance and construction operation also can cause congestion with significant delay. Where possible, such activities should be confined to periods when low volumes are anticipated, even to the extent of scheduling night or weekend work. Another useful technique is to plan and schedule maintenance operations so that all required operations in a given section and lane are accomplished at one time. This will not only benefit the motorist, but will reduce maintenance costs since traffic handling is often a very significant expense in freeway maintenance operations. In any event, adequate onsite traffic control and advance information to motorists should be provided.

Other factors of an environmental nature frequently contribute to capacity reductions and thereby congestion. Such conditions as wet pavement and sunrise and sunset aligned with driver's visibility can have a significant impact, particularly during peak periods.

4.2 ENTRANCE RAMP CONTROL

Entrance ramp control is the most widely used form of freeway traffic control. It has been applied in numerous cities in the United States as well as in other countries. Its objective is the elimination, or at least the reduction, of the operational problems resulting from freeway congestion.

Table 4.2. Capacity reduction resulting from shoulder and lane blockages, Gulf Freeway (Houston, Texas)

Blockage Location	Capacity Reduction (Percent of 3-Lane, Single Direction)
Shoulder only	33
One lane	50
Two lanes	79

Source: Reference (*14*)

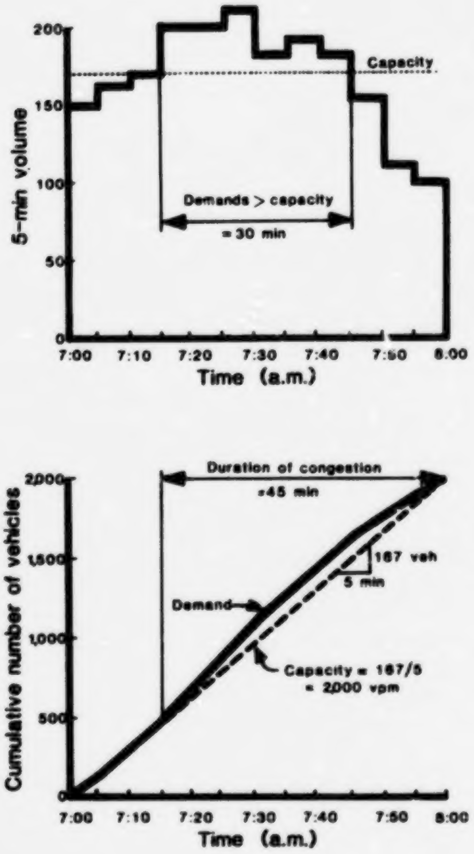


Figure 4.3. Relationship among demand, capacity, and congestion

Source: Reference (9)

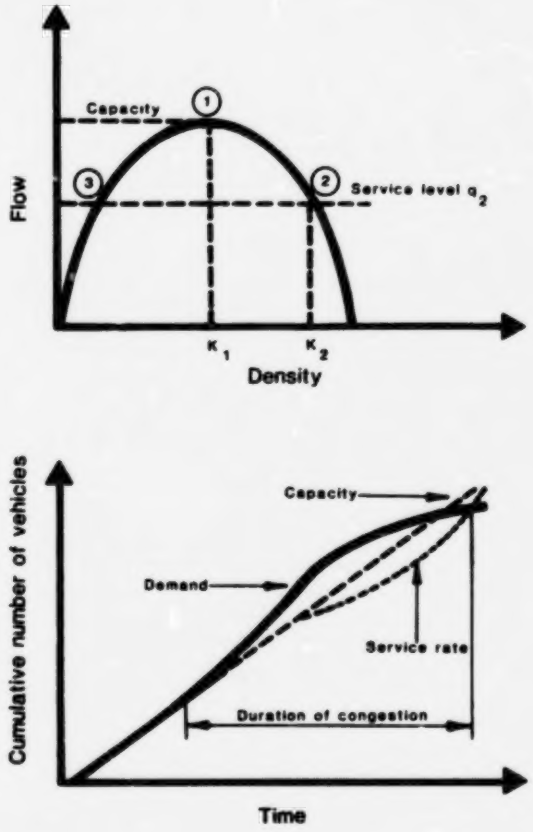


Figure 4.4. Flow-density relationship and revised relationship among demand, capacity, and congestion

Source: Reference (*138*)

99

The principle of entrance ramp control is the limiting of the number of vehicles entering the freeway so that the demand on the freeway itself will not exceed capacity. Consequently, some of the traffic desiring to use the freeway will be required to wait at the entrance ramps before being allowed to enter the freeway. Instead of waiting at the entrance ramps, some vehicles may choose not to use the freeway at all, to enter it from another location, or to enter at another time of day. Also, some drivers may decide to use public transit (if it is available) or form carpools. This traffic, which takes another route or time or mode of transportation for at least a portion of its trip, is referred to as "diverted traffic."

Thus, the intended result of entrance ramp control is to maintain uninterrupted, noncongested flow on the freeway for as long as possible by transferring the delay factor from the freeway location to the entrance ramp location, and thus diverting the excess vehicular demand to either alternate routes in the corridor, or other time periods with less demand, or other modes of transportation.

Entrance ramp control strategies which attempt to reduce entrance ramp demand generally result in some diversion of trips to other routes. Such strategies, called diversion strategies, are used in most freeway control systems in the United States. In some cases where alternate routes are not available to bypass a bottleneck condition, a nondiversion strategy may be used. In the nondiversion strategy, ramps are metered to accommodate the full traffic demand. By releasing vehicles one or two at a time, experience has shown the nondiversion strategy to be effective in reducing the friction (jockeying for position) in the area where ramp traffic merges with mainline flows. The result of reduced merging friction is that the onset of peak-hour congestion is delayed because of the ability to maintain free-flow conditions for a longer period.

An issue of concern in implementing ramp metering systems is that of equity. Benefits must accrue to both longer and shorter trips, and a nondiversion strategy used on close-in ramps may provide a viable solution.

Entrance ramp control has been found to offer several direct benefits. Generally, it provides a higher and more predictable level of service on the freeway. By maintaining noncongested freeway flow, or by at least reducing freeway congestion, this type of control improves the efficiency and safety of freeway operation. It can also improve the safety of the merging operation, particularly at entrance ramps with inadequate sight distances. Ramp metering also smoothes the input of traffic over short periods of time even without diverting traffic. In terms of safety, freeway management projects have produced remarkable accident reductions, averaging 31 percent for seven representative projects.

In addition, entrance ramp control can help achieve maximum utilization of total corridor capacity. By making traffic wait, it makes using the freeway less attractive for some trips than using either available alternate routes or the freeway at another time, or transferring to another mode of transportation. In this way, ramp control can help distribute the total traffic load among all the routes and modes of transportation in the corridor and help steady the demand within the peak periods.

Entrance ramp control can also preserve the operational efficiencies made possible by geometric improvements on the freeway. For example, the Upgrade and Control Program established in Los Angeles uses entrance ramp control for this purpose (*15*). Here, freeway capacity is increased where it is needed. Entrance ramp control then is initiated to limit the demand to the capacity of the improved freeway section. It has been proposed that new freeways should have entrance ramp control built into the system at the time of construction or reconstruction in order to limit the demand to capacity.

However, to be practical, the freeway-traffic operational problems which are eliminated or reduced by entrance ramp control must more than offset those which may be created or intensified for traffic on alternative routes. The success of entrance ramp control, then, is dependent on the extent to which the following conditions are satisfied:

- When diversion strategies are used, additional capacity (alternate routes, time periods, or modes of transportation) should be available in the corridor. The capacity should be great enough to accommodate not only the traffic to be diverted from the freeway, but also the normal level of traffic already using it. If this extra capacity is not available in the corridor, congestion will occur elsewhere, even though entrance ramp control might be preventing the congestion from occurring on the freeway. This transferred congestion might then occur on the alternate routes and in the vicinity of the entrance ramps, thus offsetting the benefits of freeway traffic control. Since ramp control measures do not create capacity, additional capacity must be added to the corridor to prevent congestion. This can be achieved in many ways such as by retiming traffic signals, installing a traffic-responsive signal system, adding turn lanes at intersections (by eliminating parking, adding a left-turn lane through use of paint striping or channelization with narrow lanes), reversible lane operation, and/or roadway widening.

  In some cases, drivers may prefer to use the freeway regardless of the capacity on alternate routes or the availability of other modes of transportation because of comfort, personal safety, and/or whatever other factors influence drivers from traveling through certain neighborhoods, or on other modes of transportation. Also, a priority system of entrance ramp control should be used to effectively realize the potential of entrance ramp control for diverting traffic to public transit and/or carpools. This system is designed to provide preferential treatment to buses and/or carpools in such a way that these vehicles are allowed to enter the freeway with little or no delay, while the other ramp vehicles are required to wait. A number of types of bus/carpool priority controls are described in subsequent sections of this chapter.

- Adequate storage space should exist at the entrance ramps. The storage situation should assure that the queues of waiting vehicles will not seriously affect nonfreeway traffic. Ramp traffic should not be allowed to back up so as to block frontage roads or surface streets. Often, queue detectors are installed on the ramp just downstream of the frontage road, surface street, or other critical point. When queue buildup across the detector is observed, vehicles are metered at a higher rate to avoid spillback of congestion into the critical area.
- Traffic patterns should be appropriate. For example, if the mainline input to a freeway section is equal to the capacity of the section, then the number of additional vehicles that can be permitted to enter the section via entrance ramps is the same as the number leaving the section via exit ramps. Thus, if the traffic pattern results in no traffic exiting the section in this manner, then theoretically no traffic can be allowed to enter the freeway from the entrance ramps. In most situations, however, this is usually not acceptable.

  Also, the potential of entrance ramp control as a means of encouraging traffic to use the extra capacity of alternate routes in the corridor is dependent on the traffic pattern. If most trips are regional in nature and only a small percentage of localized traffic exists, then little diversion will take place.
- Public acceptance is important for the success of entrance ramp control. Although the system may offer significant overall benefits to the public, it is difficult to relate these benefits to individual freeway users. A majority of the users who will be impacted by entrance ramp control will only see the delay caused by the entrance ramp signals. In announcing the beginning of an entrance ramp control system, it is important to inform the public about the basic reasons for initiating the system (severe congestion, inefficient freeway operation, etc.), a realistic expectation of the system's benefits to users (reduced delays and user costs), and the alternative choices that are available to the system users. How the system responds to the allocation of available capacity in an equitable manner must be stressed. The operation should be closely monitored and fine tuned as required to achieve these objectives, and the public should be kept informed of their achievement.

With regard to warrants for the use of entrance ramp control, the Transportation Research Board Freeway Operations Committee (Committee A3A09) has recently formulated updated warrants which shifted the terminology emphasis from "warrant" to "guidelines" (*16*). *The Manual on Uniform Traffic Control Devices* (MUTCD) (*17*) has been revised, effective March 1, 1984, to incorporate these guidelines.

The following types of entrance ramp control are in common use:

- Closure
- Ramp metering
- Traffic-responsive metering
- Gap-acceptance merge control
- Integrated ramp control

Closure

The closure of an entrance ramp during peak traffic conditions is the simplest and most positive form of entrance ramp control. It is also the most restrictive. Therefore, it is usually the least popular and it is also subject to considerable public opposition. However, it has been used successfully as part of a system in a number of cities in the United States and Japan (e.g., Houston (*18*); Los Angeles (*19*); San Antonio; Fort Worth; and Osaka and Tokyo, Japan (*20, 21*). Closure has also been effectively used in single spot improvements at entrance ramp applications, such as on freeways in Beaumont and Corpus Christi. Closure may be the appropriate measure where an entrance ramp introduces serious weaving problems. Although this type of entrance ramp control can provide the same operational benefits to freeway traffic as the other types, it lacks flexibility. Consequently, if applied inappropriately, it could result in underutilizing freeway capacity, with the consequent overloading of alternate routes.

Application. Because of its limitations, entrance ramp closure should not be considered except under the following circumstances:

- Adequate storage is not available at the entrance ramp to prevent queues of vehicles waiting to enter the freeway from interfering with surface street traffic. The closure of the entrance ramp would eliminate the storage problem.

- Traffic demand on the freeway immediately upstream of the entrance ramp is at capacity, and an alternate route with adequate capacity is available. The closure of the entrance ramp would prevent the demand from exceeding capacity on the freeway section immediately downstream from it, and it would divert the traffic demand at the ramp to an alternate route. Even if the upstream traffic demand is less than downstream capacity, the rate at which traffic could be allowed to enter the freeway might be so low that it would not be possible to control the entrance of ramp traffic without a large number of violations. In this case, it would be more practical to close the ramp in order to prevent congestion on the freeway.

With regard to the second circumstance, it should be noted that the required demand-capacity relationship could occur because of nonrecurrent congestion as well as because of recurrent conditions. Therefore, closure might be used as a response to incidents on the freeway, as is done in Japan (*20, 21*).

Methods. Methods of entrance ramp closure that have been used in current systems include the following:

- Manually placed barriers
- Automated barriers
- Signing

The experience in Detroit (*22*) and Los Angeles (*23*) has indicated that signs alone cannot effect a positive entrance ramp closure. Automated barriers such as those shown in Figure 4.5 enable an entrance to be closed and opened automatically, which would tend to increase the flexibility of closure as a means of control. Since manual placement of barriers is laborious, this approach is best suited for short-term or trial control projects.

Ramp Metering

Metering is a method of restricting traffic flow. When applied as a form of entrance ramp control, metering is used to limit the rate at which traffic can enter a freeway. Metering rates used at an entrance ramp will usually be less than a practical maximum of 750 to 900 vph and greater than a practical minimum of 180 to 240 vph. When the metering rate is not directly influenced by mainline traffic conditions, the control is referred to as "pretimed metering." This does not, however, necessarily imply the absence of vehicle detectors.

Metering Rates. The calculation of metering rates depends on the purpose for which the metering is being used. Normally, metering is used either to eliminate congestion on the freeway or to improve the safety of the merging operation as follows:

- Congestion — If the metering system is intended to eliminate or reduce congestion, the demand must be kept less than capacity. Therefore, the calculation of the metering rate at a ramp would be based on the relationship between upstream demand, downstream capacity, and the volume of traffic desiring to enter the freeway at the ramp. Downstream capacity may be determined by the merging capacity at the ramp or by the capacity of the freeway section downstream. Of course, if the sum of upstream demand and ramp demand were less than or equal to downstream capacity, metering would not be needed to prevent congestion. On the other hand, if the upstream demand alone is greater than downstream capacity, metering at the ramp would not eliminate congestion. Otherwise, the metering rate is set equal to the difference between upstream demand and downstream capacity.

For example, in the situation shown in Figure 4.6, the upstream demand is 5,100 vph, the downstream capacity is 5,400 vph, and the ramp demand is 500 vph. Since the total demand (5,600 vph) is greater than the downstream capacity, congestion will occur on the freeway unless the total demand is limited to capacity. And, since the upstream demand is less than downstream capacity, ramp metering might be a feasible solution. Therefore, if a metering rate equal to the difference between upstream demand and downstream capacity (300 vph) is used, the freeway would be able to accommodate the upstream demand and maintain noncongested flow while also handling 300 vph of the ramp demand.

However, the ultimate test of the feasibility of ramp metering at a rate of 300 vph would involve consideration of the following questions:

- ☐ Is adequate additional capacity available in the corridor for the 200 vph that are likely to be diverted? And, if so, is it likely that the 200 vph would utilize that extra corridor capacity? If not, capacity would have to be added to the corridor and/or made more attractive for this number of vehicles per hour to be diverted. Otherwise, ramp metering would solve only the problem on the freeway.
- ☐ Is adequate storage available at the ramp to accommodate the queue of vehicles that would have to wait at the ramp before entering the freeway? If adequate storage could not be provided at the ramp, alternatives to be considered would be closure of the ramp, or metering at other ramps upstream to reduce upstream demand, which would

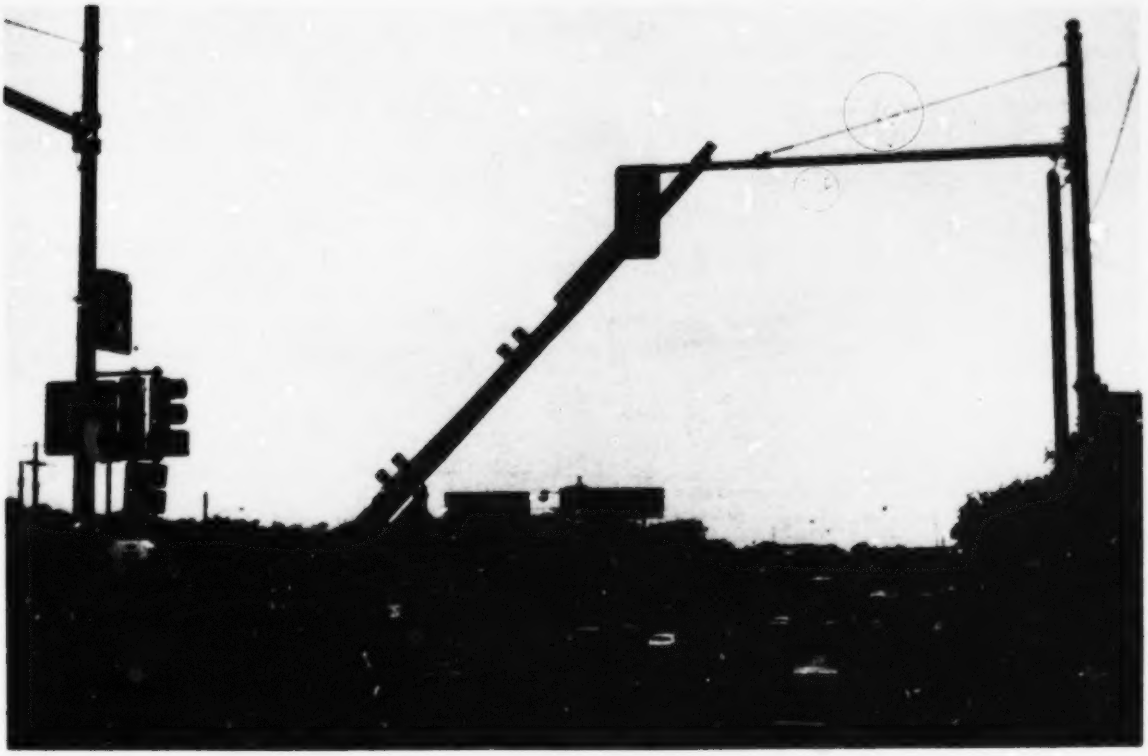


Figure 4.5. Entrance ramp closure by means of automated barriers

in turn permit a higher metering rate and require less storage at the ramp.

  - Is the specified metering rate (300 vph) too restrictive? If so, consideration should be given to closing or metering other ramps upstream to reduce upstream demand, which would permit a higher metering rate at the ramp. However, metering other ramps upstream might lead to the underutilization of the freeway.

- Safety — If metering is to be used only as a means of improving the safety of the merging operation, then the metering rate is simply set at a maximum consistent with merging conditions at the particular ramp. The primary safety problem of the merging operation is incidence of rear-end and lane-change collisions caused by platoons of vehicles on the ramp competing for gaps in the freeway traffic stream. Therefore, metering is used to break up these platoons and to enforce single-vehicle entry. To do this, the metering rate selected must assure that each vehicle has time to merge before the following vehicle approaches the merge area. The time it takes a vehicle to merge depends on the following factors:
  - Distance the vehicle is stopped from the freeway
  - Geometrics of the ramp (grade, sight distance, and length of the acceleration lane)
  - Type of vehicle
  - Availability of acceptable gaps in the freeway traffic stream

If the average time to merge is 6 sec, the metering rate would be 10 vpm or 600 vph.

Pretimed Metering

System Components. Pretimed metering is the simplest form of entrance ramp metering. Essential components of a pretimed metering system include the following:

- Ramp metering signal — Usually a standard 3-section (red-yellow-green), or 2-section (red-green), signal display which controls the ramp traffic.
- Local controller — Frequently a standard pretimed

controller, perhaps with sufficient logic to vary metering rates by time of day and/or accept input from checkin and queue detectors.

- Advance ramp control warning sign with flashing beacon — A sign which indicates to traffic approaching the ramp that it is being metered. In California, a blank-out type "METER ON" sign is used at many installations in lieu of the flashing beacon.

Optionally, and depending on the purpose of the control and the strategy employed, the following components are sometimes included:

- Checkin (demand) detector — In some applications of pretimed metering (*24*) a checkin detector is placed on the approach to the ramp metering signal so that the signal will remain red until a vehicle is detected at the stop line, as shown in Figure 4.7. When a vehicle is detected by the checkin detector, the ramp metering signal will change to green, provided the minimum red time has elapsed. With this type of operation, it is desirable to have a minimum metering rate (e.g., 3 vpm) at which the signal is set in case there is no detector actuation, because of possible detector failure or because of vehicles stopping too far back from the stop line to actuate the detector.
- Checkout (passage) detector — In some systems, a checkout detector has been used to ensure single-vehicle entry. When a vehicle is permitted to pass the ramp metering signal, it is detected by the checkout detector, which is installed just beyond the stop line (usually about 8 ft past it). The green interval is then terminated as soon as the vehicle is sensed by the checkout detector. In this way, the length of the green interval is made sufficient for the passage of only one vehicle.
- Queue detector — In some pretimed metering systems, a queue detector is used to prevent ramp traffic from blocking frontage roads or surface streets. The queue detector is placed at a strategic point on the ramp, or on the frontage road, in advance of the ramp metering signal. As soon as it senses a vehicle occupying the loop for a selectable period of time, indicating that the queue of vehicles waiting at the ramp metering signal is sufficient to interfere with traffic on the frontage road or surface streets, a higher metering rate is used to shorten the queue length.
- Merge detector — A device which senses the presence of vehicles in the primary merging area of the ramp and freeway mainlanes.

The location of these components on a ramp is illustrated in Figures 4.7 and 4.12. Figure 4.8 shows ramp metering signals and advance warning signs that have been used. The location and configuration of detectors are discussed in Chapter 5 of this Handbook. Also, for a discussion of standards for various system components refer to the recommended practice for freeway entrance ramp displays prepared by the Institute of Transportation Engineers (ITE) (*25*).

System Operation. In the operation of a pretimed metering system, the ramp signal operates with a constant cycle in accordance with a metering rate prescribed for the particular control period. However, timing the red, yellow, and green intervals of the cycle (many systems use ramp signals which have only red and green intervals) depends on the type of metering used, single-entry metering or platoon metering.

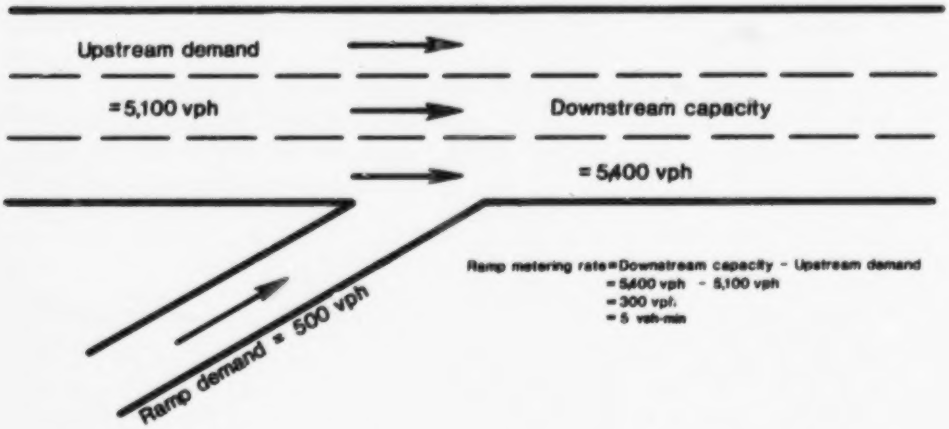


Figure 4.6. Example of pretimed, entrance ramp metering rate calculation

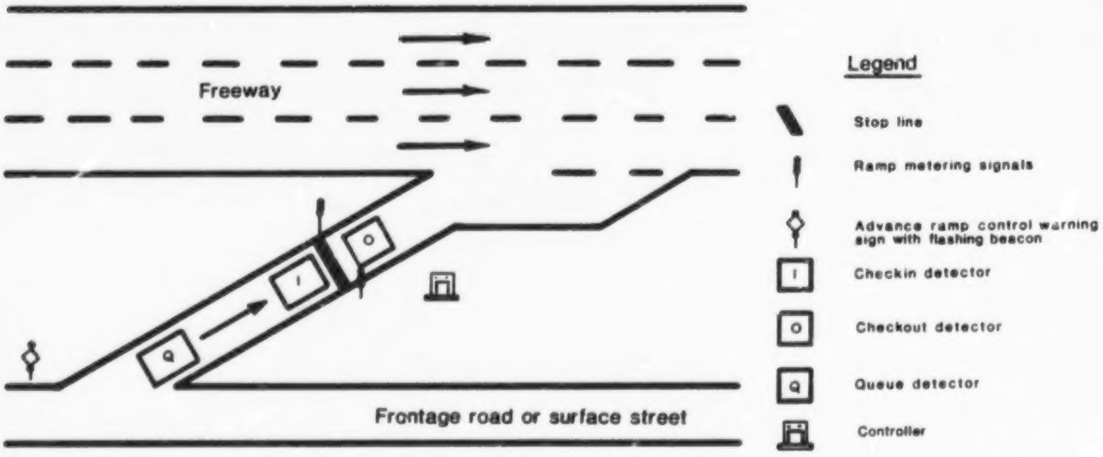


Figure 4.7. Layout of pretimed, entrance ramp metering system

- Single-entry metering — In the case of single-entry metering, the ramp metering signal is timed to permit only one vehicle to enter the freeway per green interval. Therefore, the green-plus-yellow (or just green if yellow is not used) interval is just long enough (usually about 3 sec) to allow one vehicle to proceed past the signal. Then red is used for the remainder of the metering cycle. For instance, if a metering rate of 600 vph or 10 vpm were to be used, the green-plus-yellow interval would be 3 sec and a red interval of 3 sec would be used. If the metering rate were 300 vph, or 5 vpm, a green-plus-yellow interval of 3 sec and a red interval of 9 sec would be used.
- Platoon metering — When metering rates greater than 900 vph are required, platoon metering, which permits the release of 2 or more vehicles per cycle, must be used to achieve such high metering rates. For pretimed platoon metering, the cycle length is determined on the basis of the desired metering rate and the average number of vehicles to be released per cycle. For example, in the case of a metering rate of 1,080 vph, or 18 vpm, and a release of 2 vehicles per cycle, 9 cpm would be required. Therefore, the cycle length would be 6.67 sec. Similarly, if a release of 3 vpc was used instead, the cycle length would be 10 sec. However, the timing of the cycle intervals (i.e., green, yellow, red) would depend on the form of platoon metering used, tandem or 2-abreast.

In the case of tandem metering, the vehicles are released one behind another. Therefore, the green-plus-yellow time is made long enough to permit the clearance of the desired number of vehicles per cycle. A yellow interval should be used to minimize the rear-end collision potential. Thus, for the 6.67-sec cycle with two-vehicle platoons, a 4.67-sec green-plus-yellow and a 2-sec red might be used. And for the 10-sec cycle with 3-vehicle platoons, a 7-sec green-plus-yellow and a 3-sec red might be used. Experience indicates that two-vehicle platoons can be handled satisfactorily and that three-vehicle platoons are a practical maximum. In either case, a maximum metering rate of 1,100 vph can be expected (*26*).

With two-abreast metering, two vehicles are released side by side per cycle. This form of metering requires two parallel lanes on the entrance ramp plus a sufficient distance beyond the ramp metering signal for the two vehicles to achieve a tandem configuration before merging with freeway traffic. The more common practice in two-lane situations is to stagger the release — one from the left lane followed by one from the right. The timing of the cycle intervals for multiple-lane metering is similar to that for single-entry metering in that the green-plus-yellow interval is just long enough (usually about 3 sec) to allow one vehicle in each lane to proceed past the ramp metering signal. The remainder of the cycle is red. With such metering, maximum metering rates of about 1,100 vph may be achieved.

Compared to single-entry metering, platoon metering has a number of disadvantages such as greater driver confusion, greater probability of rear-end accidents, and greater possibility of disrupting freeway flow. Therefore, single-entry metering should always be given first consideration, and platoon metering

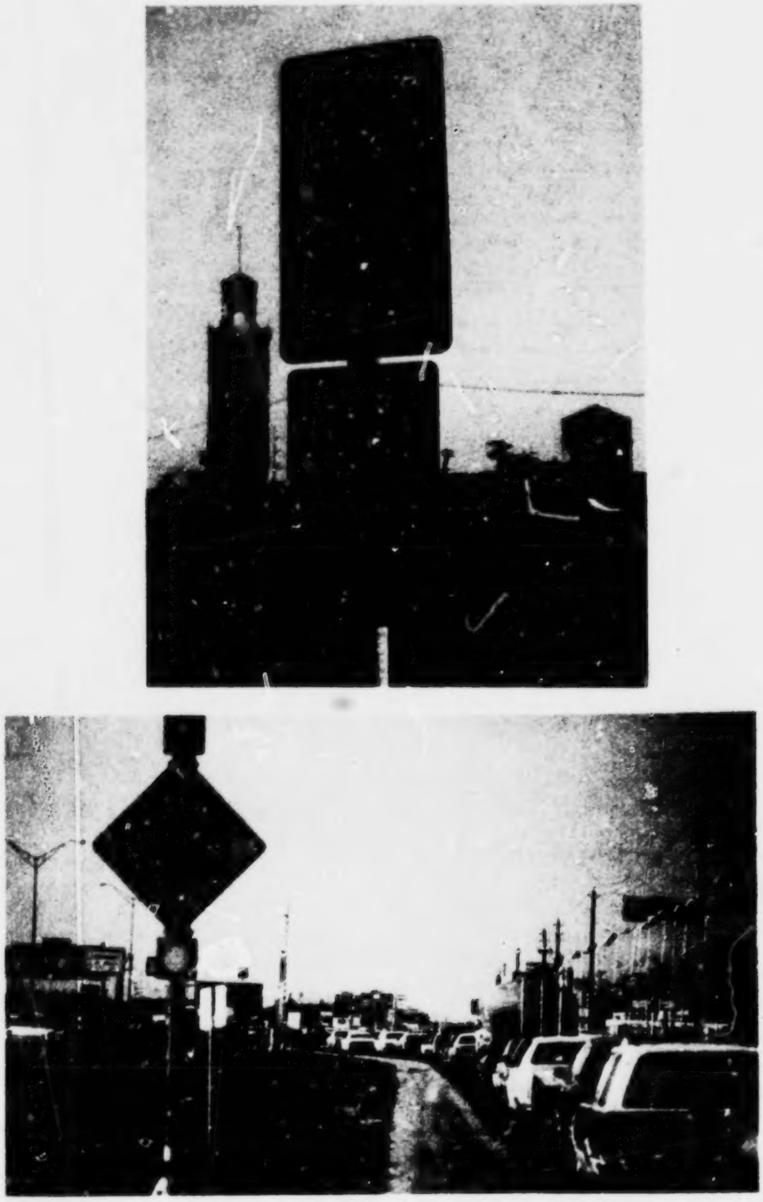


Figure 4.8. Ramp metering signals and advance ramp metering systems

should not be used unless it is necessary to achieve higher metering rates.

System Evaluation. Benefits of pretimed metering systems, when compared to the situation without control, are usually expressed in terms of the following:

- Higher freeway speeds
- Less delay to freeway users
- Higher freeway-service volumes
- Reduced travel time to freeway users

- Safer merging operation (fewer rear-end and lane-change collisions)
- Reduced operating costs to freeway users
- Reduced fuel consumption and emissions

Benefits that have been reported for some ramp metering installations are summarized in Table 4.3. It has been shown that entrance ramp control can be extremely cost effective (*27*). Experience in California (*23, 28*) has indicated that the biggest net gain in benefits is realized in going from no control to pretimed metering, and that any increases in control sophistication quickly run into diminishing returns.

Pretimed metering offers both advantages and disadvantages. The most important advantages are that it gives the driver a dependable situation to which he can readily adjust, and lower costs associated with pretimed metering. The major disadvantage is that the system can neither respond automatically to significant changes in demand, nor adjust to unusual traffic conditions resulting from incidents. Because of this inability to automatically respond to changes in traffic conditions and the relative difficulty of dissipating resultant congestion, pretimed metering rates have usually been set so that operation would be at volumes slightly below capacity.

Traffic-Responsive Metering

In contrast to pretimed metering control, traffic-responsive metering is directly influenced by the mainline and ramp traffic conditions during the metering period. Metering rates are selected on the basis of real-time measurements of traffic variables indicating the current

Table 4.3. Summary of reported benefits of entrance ramp metering systems

Location	Length (Mi)	Time Period (Hr)	Travel Time Improvement (Percent)	Congested Freeway Travel, Minute-Mile, Reduction (Percent)
Minneapolis (Minnesota)				
I-35W				
Inbound	16.6	7:15-8:15 a.m.	34	95
		6:30-9:30 a.m.	14	100
Outbound	12.7	4:30-5:30 p.m.	19	59
		3:30-6:30 p.m.	19	92
Chicago (Illinois)				
Eisenhower Expressway				
Inbound	9.4	2-hr a.m. peak	9	22
		4-hr a.m. peak	5	23
Los Angeles (California)				
Santa Monica Freeway				
Inbound	13.5	6:30-9:30 a.m.	40	100
Houston (Texas)				
Gulf Freeway				
Inbound	6	7:00-8:00 a.m.	60	66
Los Angeles (California)				
Harbor Freeway				
Outbound	4	3:45-6:15 p.m.	55	80
Detroit (Michigan)				
Lodge Freeway				
Inbound	6	2:30-6:30 p.m.	33	89
Toronto (Canada)				
Queen Elizabeth Way (QEW)				
Inbound	3.9	7:00-9:00 a.m. (good conditions)	45	45
		7:00-9:00 a.m. (poor conditions)	59	40

Source: Reference (*29*)

relation between upstream demand and downstream capacity.

Fundamental Traffic Flow Relationships. In order to determine or predict demand-capacity conditions on the basis of real-time measurements of traffic variables, a description or model of traffic flow is necessary. Most frequently used as indicators of operating conditions for traffic-responsive metering are functional relationships between flow rate, q; space-mean speed, u; and density, k (*30*).

A typical form of the relationship among q, u, and k is depicted in Figure 4.9. It is usually more convenient to describe the model of Figure 4.9 by three separate relationships (as shown in Figure 4.10), which can be summarized as follows:

- At zero density, or when no vehicles are on the roadway, the flow rate is zero, and traffic is permitted to travel at its free speed, u_f.
- As density increases to a value, k_m, the flow rate increases to a maximum value, q_m, which is the capacity of the roadway, and speed decreases to a value, u_m.
- As density increases from a value, k_m, to a maximum value, k_j (jam density), the flow rate decreases to zero because the roadway is blocked with too many vehicles for traffic to move.

The values of q_m, u_f, u_m, k_m, and k_j — and the shapes of the curves — depend on several factors which include geometrics of the roadway, composition of traffic, and weather conditions. Therefore, these values may be different for different sections of the roadway, and each section may have more than one set of these values. Although these are theoretical relationships based on the assumption of uniform traffic flow, the trends expressed by these relationships do exist (*31*).

Basic Strategy. As explained earlier, congestion occurs whenever demand exceeds capacity. Therefore, as

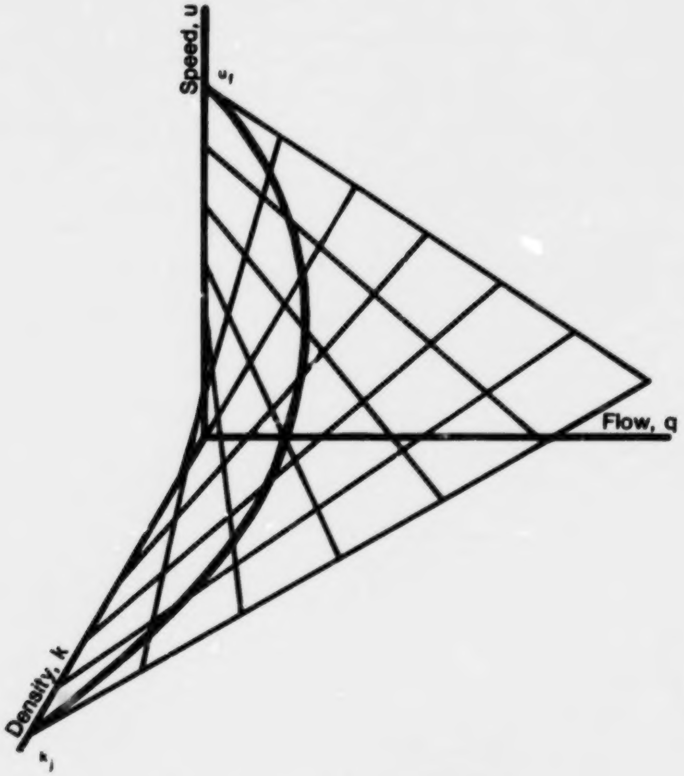


Figure 4.9. General traffic flow model

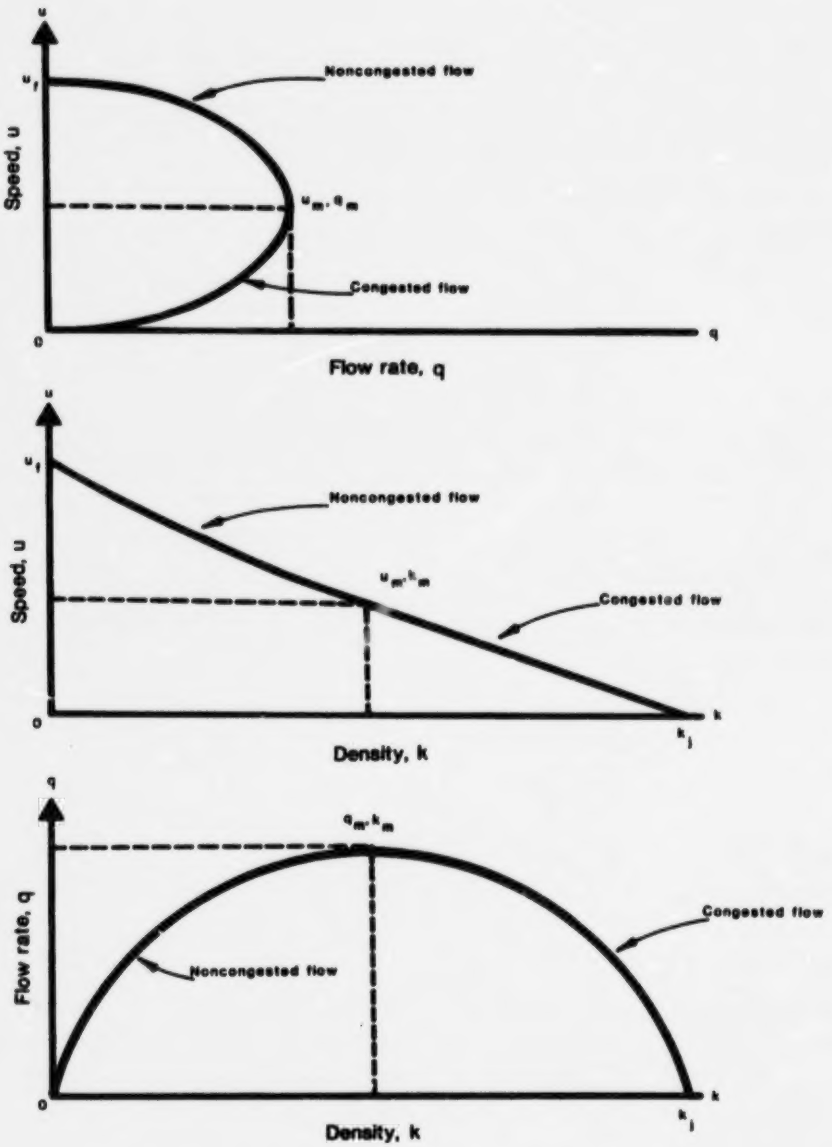


Figure 4.10. Fundamental flow rate-speed-density relationships

indicated in Figure 4.10, the values of q_m, u_m, and k_m define boundaries between noncongested flow and congested flow. The purpose of metering is to prevent or reduce congestion, or, in other words, to keep the values of the fundamental traffic flow variables at levels that define points on the uncongested-flow portions of the traffic flow curves. Thus, the basic strategy of traffic-responsive metering is as follows:

- Obtain real-time measurements of traffic variables on the freeway
- On the basis of these measurements, determine where on the fundamental traffic flow curves the freeway section is operating with respect to capacity
- Determine the maximum ramp metering rate at which vehicles can be permitted to enter the freeway

A refinement which is often made to this strategy is to select the traffic flow curves on the basis of traffic composition and weather conditions.

Lane occupancy (a surrogate measure for density) and flow rate (volume) are the two traffic variables generally used to describe freeway traffic conditions for traffic-responsive metering. These are the control parameters usually used because they can be measured in real time using vehicle detectors.

Several variations on the basic strategy of traffic-responsive metering utilize different combinations of traffic variables. Although most are reported as having positive effects on freeway operations, none has been generally accepted as being superior to the others. In fact, new strategies are still being formulated to find better modes of control. However, the principal traffic-responsive strategies remain the following (*27*):

- Demand-capacity control
- Occupancy control

Demand-Capacity Control. Demand-capacity control features the selection of metering rates on the basis of a real-time comparison of upstream volume and downstream capacity. The upstream volume is measured in real time and compared with either a preset value of downstream capacity determined from historical data or a real-time value computed from downstream volume measurements. To be most effective, the downstream capacity used should account for the effects on capacity of weather conditions, traffic composition, and incidents.

The difference between the upstream volume and the downstream capacity is then determined and used as the allowable entrance ramp volume. This ramp volume is expressed as a metering rate to be used during the next control interval (usually 1 min). If the upstream volume is greater than the downstream capacity, a minimum metering rate is used (e.g., 3-4 vpm). Of course, theoretically, if the upstream volume were greater than the downstream capacity, a zero metering rate, or ramp closure, should be used in order to prevent congestion. It has generally been found that metering rates lower than 3 vpm are not effective, because vehicles waiting at the ramp will judge the ramp metering signal to be malfunctioning and proceed through on red.

Since a low upstream volume could occur in congested as well as noncongested flow, volume alone does not indicate degree of congestion. Therefore, an occupancy measurement also is usually made to determine whether noncongested or congested flow prevails. If the occupancy measurement is above a preset value (e.g., 18 percent, as used in Los Angeles) (*28*), which is determined from historical data, congested flow would be assumed to exist and a minimum metering rate used.

Occupancy Control. Occupancy control utilizes real-time occupancy measurements generally taken upstream of the entrance ramp. One of a number of predetermined metering rates is selected for the next control interval (usually 1 min) on the basis of occupancy measurements taken during the current control interval. For a given entrance ramp, the metering rate to be used for a particular value of occupancy would be based on a plot of historical volume-occupancy data collected at each measurement location. (An example of a typical plot is shown in Figure 4.11.) From such a plot, an approximate relationship between volume and occupancy at capacity is determined. Thus, for each level of occupancy measured, a metering rate can be computed which corresponds to the difference between the predetermined estimate of capacity and the real-time estimate of volume. If the measured occupancy is greater than, or equal to, the preset capacity occupancy, a minimum metering rate would be selected instead of a zero rate or ramp closure. This choice would be based on effective and practical entrance ramp control considerations, as explained earlier for demand-capacity control.

Details of traffic-responsive metering strategies which have been applied in a number of cities have been summarized in Table 4.4. In addition, platoon metering and 2-abreast metering strategies apply to traffic-responsive metering as to pretimed concepts.

System Components. A traffic-responsive metering system contains the same components as described for pretimed metering. These include ramp metering signal(s), local controller, advance warning sign with flashing beacon, and detectors. The local controller unit for traffic-responsive metering requires additional logic over and above that required for pretimed metering in order to monitor traffic variable measurements, select or calculate metering rates, and respond to override-type conditions such as excessive queues. Queue, checkin, checkout, and merge detectors are normally also included in traffic-responsive metering systems.

The typical location of these components on a ramp is shown in Figure 4.12, and the configurations of some of the traffic-responsive systems that have been installed and are in operation (*20, 27, 28*) are summarized in Table 4.5. The location and configuration of detectors are discussed in Chapter 5. Also, for a discussion of standards for various components, the reader is referred to the recommended practice for freeway entrance ramp control displays prepared by the Institute of Transportation Engineers (ITE) (*25*).

Some traffic-responsive metering systems have also included detectors used to determine traffic composition and weather conditions (*21, 28*). Input from these detectors enables the system to account for the effects of these factors on traffic flow.

System Operation. The operation of a traffic-responsive metering system is similar to that of a pretimed metering system, except in regard to the following:

- Metering rate selection — Single-entry metering is normally used to time the red-yellow-green (or red-green) intervals for a given metering rate. However, if high metering rates (e.g., greater than 13 vpm), are required, platoon metering might be used. Both single-entry metering and platoon metering should not be used at any one ramp.

  Metering-rate selection — In a traffic-responsive metering system, the selection is based on real-time measurements of traffic variables which describe traffic flow conditions on the freeway. The control interval, which is the time period during which a selected metering rate remains in effect, is much shorter for a traffic-responsive metering system (e.g., 1 min) than for a pretimed metering system (e.g., 30 min, 1 hr, or the entire peak period).

In Fort Worth, a system of mutually coordinated ramp meter control is used to integrate a small system of successive ramps. The controller assembly at the downstream freeway mainlane bottleneck location is designated as the master and establishes the highest allowable metering rate for the upstream ramps based on mainlane occupancy at the bottleneck. Using radio and/or hardwire interconnect, the master directs the upstream controller assemblies to operate at a metering rate which is at least as restrictive as that imposed by the master. Five levels of rates are provided, one of which permits free operation.

- Override features — Override features of a traffic-

Table 4.4. Summary of various traffic-responsive, entrance ramp metering strategies

Location	Type of Control	Method of Determining Metering Rate	Overrides
San Diego (California)	Occupancy	Occupancy measured on all mainline lanes upstream of the merge area. From these occupancy measurements, one of 3 metering rates (10, 6 to 7, and 4 vpm) selected	None
Detroit (Michigan) (Texas Transportation Institute)	Demand capacity	Flow measured upstream of the ramp compared to the predetermined down stream capacity every minute, and the metering rate (4 vpm) calculated accordingly	Queue, merge area, and maximum red
Chicago (Illinois)	Occupancy	One of 5 metering rates (13, 10, 8, 6, and 4 vpm) selected on the basis of 1-min average occupancy measured in mainline lane upstream	Queue and merge area
Houston (Texas)	Demand capacity	Metering rates selected once every minute on the basis of volume-capacity comparisons of 2 bottlenecks in the control section and volume and speed checks at the ramps	Queue, merge area, and maximum red
Minneapolis (Minnesota)	Volume capacity	Metering rates selected on basis of upstream, downstream, and at-ramp volume and occupancy measurements compared with threshold values established for each ramp; metering rates ranging from 3 to 14 vpm	Weather conditions — one for rain and another for snow

Source: Reference (*27*)

Table 4.5. Summary of various traffic-responsive, entrance ramp metering configurations for system operation

Location	Control Parameter Detector	Checkin Detector	Checkout Detector	Merge Detector	Queue Detector
San Diego (California)	Occupancy measured on all lanes upstream of the merge area	X			
Detroit (Michigan) (Texas Transportation Institute)	Volume measured on all lanes upstream of entrance ramp	X	X	X	X
Chicago (Illinois)	Occupancy and volume measured on one mainline lane upstream of entrance ramp	X	X		X
Houston (Texas)	Volume and speed measured on all lanes upstream of entrance ramp	X	X	X	X
Minneapolis (Minnesota)	Occupancy and volume measured on all lanes upstream and downstream and at the ramp	X		X	X

Source: Reference (*27*)

responsive system adjust metering rates in accordance with certain operational considerations, as follows:

- Continued actuation of the queue detector — Indicates that the queue of vehicles waiting at the ramp metering signal is approaching the frontage road or surface street and is likely to interfere with traffic on either or both. Therefore, a higher metering rate should be used to shorten the queue length.
- Actuation of the merge detector — Indicates that a vehicle is still in the merge area. Therefore, in the case of single-entry metering, subsequent green intervals are preempted until the vehicle merges.
- No actuation of the checkout (passage) detector after a green interval — Indicates that a vehicle has missed the green signal. Therefore, the ramp metering signal is returned to or left in green.
- Continued actuation of the queue detector with no actuation of the checkin (demand) detector (in the case of systems in which the ramp metering signal rests in red) — Such a condition would indicate that a vehicle on the ramp has stopped short of the checkin detector. Therefore, the ramp

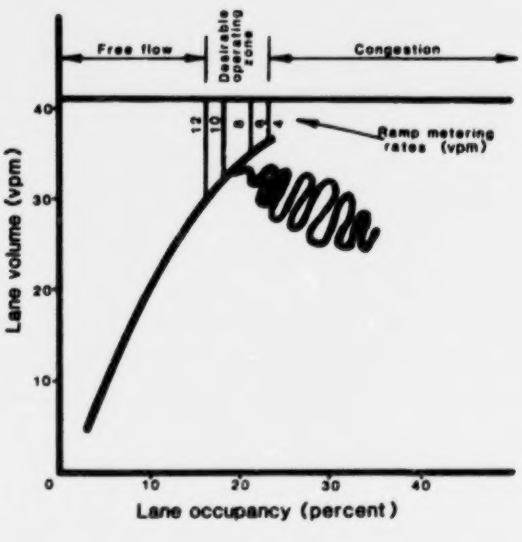


Figure 4.11. Typical volume-occupancy plot used in the calculation of entrance ramp metering rates. Chicago (Illinois)

Source: Reference (*137*)

metering signal is turned to green to allow this vehicle to proceed.

System Evaluation. As with pretimed metering, the following benefits have been experienced with traffic-responsive systems:

- Higher freeway speeds
- Less delay to freeway users
- Higher freeway-service volumes
- Reduced travel time to freeway users
- Safer merging operations
- Reduced operating costs to freeway users
- Reduced fuel consumption and emissions

Traffic-responsive metering has likewise been found to be relatively cost-effective, producing improvements that are generally 5 to 10 percent greater than those of pretimed metering. With incremental costs only in the 10 to 15 percent range, traffic-responsive metering is considered to be a cost-effective approach. Benefits that have been reported for some traffic-responsive metering systems are summarized in Table 4.6.

The primary advantage of traffic-responsive metering is that it automatically adapts to changes in traffic flow. The metering system helps to minimize the adverse effects caused by short-term variations in traffic demand and reductions in capacity caused by incidents.

Gap-Acceptance Merge Control

The merge-control concept of entrance ramp metering is intended to enable a maximum number of entrance ramp vehicles to merge safely without causing significant disruptions to freeway traffic. The concept involves maximum utilization of gaps in the traffic stream of the freeway lane into which ramp vehicles are to merge. It does not, however, involve the calculation of ramp metering rates in accordance with the demand-capacity constraint. Instead, the problem is merely one of inserting entrance ramp vehicles into freeway gaps.

Basic Concepts. The concepts of gap acceptance at freeway entrance ramps are important in describing the interaction of the freeway and ramp traffic. It is assumed that the ramp driver measures each gap in the adjacent freeway lane and compares it with an acceptable gap which he/she judges as large enough for a safe merge.

Table 4.6. Summary of reported benefits of traffic-responsive freeway ramp metering systems

			Travel Time	Accidents				
Location	Number of Ramps Used in Evaluation	Change (Veh-Hr/Yr)	Annual Savings (Dollars)	Annual Change	Annual Savings (Dollars)	Other Effects	Assumptions	Increase in Annual Net Benefits per System (Dollars)
San Diego (California)	2	N/A		N/A		Reduction in congestion on mainline and in rear-end ramp collisions. Easier merging operation.		
Detroit (Michigan)	8	−225,000	+675,000	N/A		High meter violation rate.	250 working days per year. Value of time equals $3 per veh-hr	675,000
Chicago (Illinois)	8	−64,000	−192,000	−51	+39,300	Some permanent diversion to alternate routes.	250 days on which benefits achieved. Value of time equals $3 per veh-hr $770 per accident.	231,300
Houston (Texas)	8	−72,670	+218,000	−40	+24,000	Reduction in vehicle-operating costs equal $18,400. Level of service increased.	$3 per veh-hr $600 per accident.	260,400
Minneapolis (Minnesota)	−39	N/A		−115	N/A	Average speeds during peak periods increased on the order of 10 mph. Reduction in accidents is average for 9 years of operation as compared to 2 years prior to system activation.		

Source: Reference (*27*); table adapted/updated

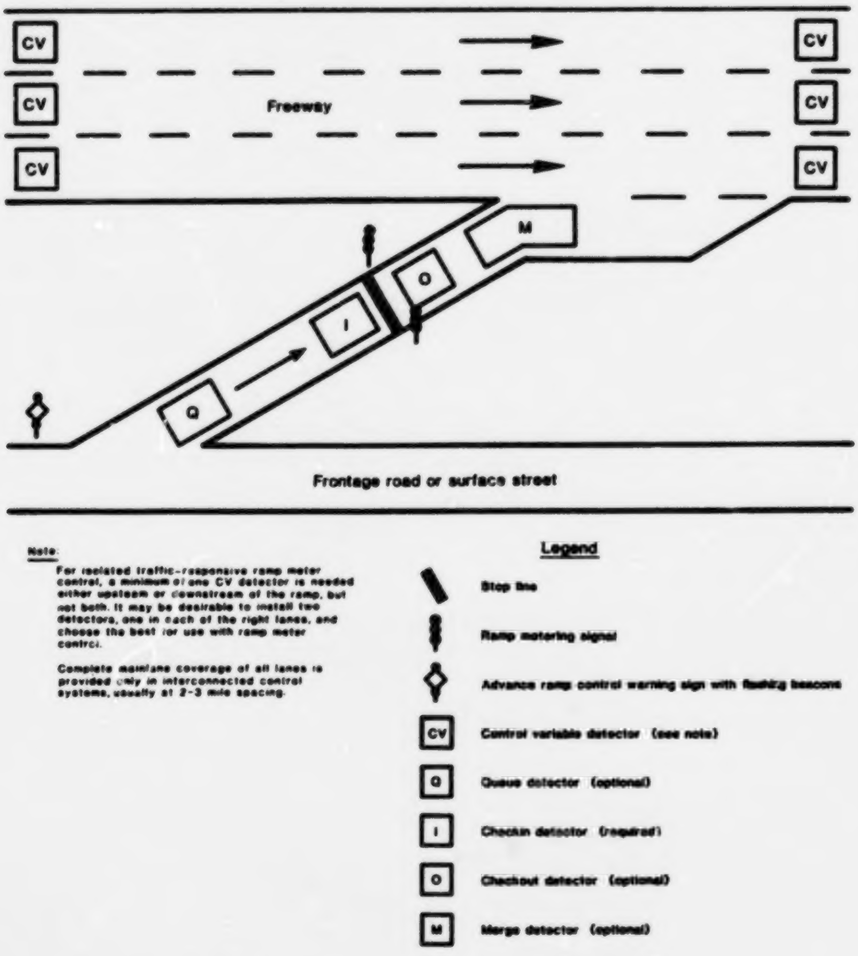
The minimum acceptable gap is dependent on several factors, such as the following (*32*).

- Entrance ramp and freeway geometrics
- Vehicle performance characteristics
- Driver behavior
- Traffic conditions
- Weather conditions

Merge-control systems are designed to improve the merging operation at the entrance ramp by providing the driver with the information needed to coordinate in time and space entry onto the freeway. These systems operate according to the following basic guideline procedures:

- Detection of an acceptable gap on the freeway into which a ramp vehicle could merge
- Projection of the arrival of the acceptable gap at the merging point of the entrance ramp
- Release of the ramp vehicle in sufficient time to accelerate and merge into the moving gap

System Components. Gap-acceptance merge-control systems use many of the same components as described for pretimed metering, to include ramp metering signals, local controller, advance warning sign with flashing beacon, and detectors. A mainlane gap/speed detector is located in the shoulder lane of the freeway upstream of the ramp merge to provide data from which the controller unit can determine presence and speed of


CV
CV
CV
CV
CV
CV
Freeway
M
O
I
Q
Frontage road or surface street
Legend
Stop line
Ramp metering signal
Advance ramp control warning sign with flashing beacons
CV
Control variable detector (see note)
Q
Queue detector (optional)
I
Checkin detector (required)
O
Checkout detector (optional)
M
Merge detector (optional)

Note:

For isolated traffic-responsive ramp meter control, a minimum of one CV detector is needed either upstream or downstream of the ramp, but not both. It may be desirable to install two detectors, one in each of the right lanes, and choose the best for use with ramp meter control.

Complete mainlane coverage of all lanes is provided only in interconnected control systems, usually at 2-3 mile spacing.

Figure 4.12. Layout of traffic-responsive, entrance ramp metering system

114

available gaps in which to insert merging ramp traffic. Queue, checkin, checkout, and merge detectors are normally also included in gap-acceptance merge-control systems.

Another override-feature component which might be added to the system is a slow-vehicle detector, which senses the presence of a slow-moving vehicle on the entrance ramp between the ramp metering signal and the merge detector. The typical location of these components on an entrance ramp is shown in Figure 4.13. Also, for a discussion of standards for various system components, the reader is referred to the tentative recommended practice for freeway entrance ramp control displays prepared by the Institute of Transportation Engineers (ITE) (*25*).

System Operation. A gap-acceptance merge-control system does not normally operate in accordance with a constant metering rate for a specified control interval as do pretimed and traffic-responsive metering systems. Instead, it operates in response to the availability of acceptable gaps in the lane of the freeway into which ramp vehicles are to merge.

Usually, the system is designed to operate in a single-entry metering mode, with the ramp metering signal resting on red when no vehicles are waiting on the ramp. Experience on the Gulf Freeway in Houston (*33*) has indicated that it is usually not desirable to operate the ramp metering signal in either of the following two ways:

- If it gives a green indication at the proper time, whether or not there is a vehicle waiting
- If it normally rests on green when there are no vehicles waiting

Procedures can be summarized as follows for the nominal operation of a gap-acceptance merge-control system, with single-entry metering and the ramp metering signal resting on red:

- A vehicle stops at the ramp metering signal and actuates the checkin detector.
- The controller begins to measure gaps and vehicle speeds which are sensed by the gap/speed detector which is located upstream from the ramp in the lane of the freeway into which ramp vehicles are to merge.
- The controller compares each measured gap to a preset minimum gap size to determine whether or not it is an acceptable gap.
- If a gap is not acceptable, the controller considers the next gap. If it is acceptable, the controller computes the time at which the vehicle at the ramp metering signal should be released in order to arrive at the merge point at the same time as does the acceptable gap. This calculation involves the following factors:
  - Speed of the traffic flow measured in the lane of the freeway into which ramp vehicles are to merge
  - Distance of the gap/speed detector location from the merge point
  - Predetermined ramp travel time of a vehicle stopped at the ramp metering signal to the merge point
- At the proper instant, the controller causes the ramp metering signal to change to green.
- The ramp metering signal remains on green for a fixed interval long enough to release a single vehicle. Then, it changes to yellow for a short fixed interval before it changes to red. (Where permitted by state law, the yellow interval may be omitted.) The green-plus-yellow (or green only) interval is usually about 3 sec long. It is necessary that the ramp metering signal remain on red long enough to give the next vehicle in line time to pull up to the signal. Thus, the minimum length for a full green-yellow-red (or green-red) cycle should be 4 to 5 sec.

The operation of the override features of a gap-acceptance merge-control system is essentially the same as that for a traffic-responsive metering system. However, a gap-acceptance merge-control system may have the following additional override features:

- Low-speed, fixed-rate metering — When congested flow develops on the freeway, small space headways between successive vehicles constitute large time headways because of the low speeds. For example, if traffic on the freeway should come to a complete stop, the measured time headways would be infinitely large. Thus, unless an appropriate override were provided, the controller would release a number of entrance ramp vehicles to enter the freeway during the congested flow, a response which would be contrary to the objective of improving freeway operations. Therefore, if the speed of the freeway traffic drops below a preset value (e.g., 25 mph) ramp vehicles are metered at a minimum fixed rate (usually 3 to 4 vpm).
- Slow-vehicle red-interval extension — At entrance ramps where there are relatively high percentages of trucks and buses, it might be desirable to make special allowances for their performance characteristics. Therefore, a slow-vehicle detector may be provided to measure the travel time of vehicles from the ramp metering signal to its location. If the travel time is greater than a preset value, the ramp metering signal is held on red until the vehicle has cleared the merge detector or until the merge detector is actuated.

System Evaluation. Benefits to be realized from a gap-acceptance merge-control system are similar to those of a traffic-responsive metering system. A study conducted by the Texas Transportation Institute (*34*), which compares a gap-acceptance merge-control system with a demand-capacity-control, traffic-responsive metering system, has reported the following results:

- Gap-acceptance merge control resulted in a higher percentage of ramp-metering-signal violations by ramp vehicles, which was probably due to its irregular pattern of operation and longer queue delays (metering rates ranged from 1 veh/4 sec to 1 veh/25 sec).
- Gap-acceptance merge control resulted in lower travel times from the ramp metering signal to the merge area, which indicates a smoother merging operation.
- Demand-capacity control resulted in higher metering rates and higher peak-hour entrance ramp volume.

In general, for entrance ramps that have well-designed geometrics, a gap-acceptance merge control is less cost-effective than either pretimed or traffic-responsive metering systems. However, gap-acceptance control might

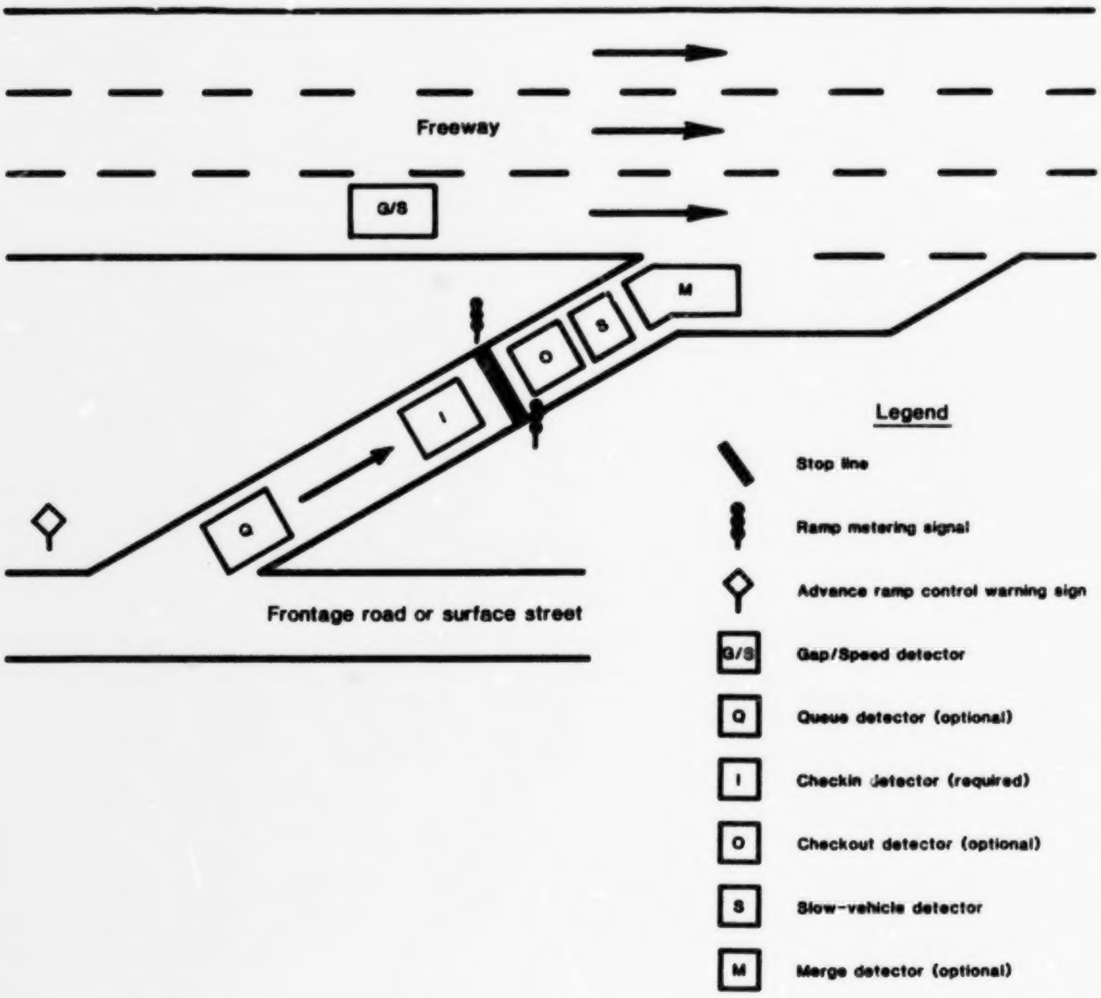

Freeway
G/S
M
S
O
I
Q
Frontage road or surface street
Legend
Stop line
Ramp metering signal
Advance ramp control warning sign
G/S Gap/Speed detector
Q Queue detector (optional)
I Checkin detector (required)
O Checkout detector (optional)
S Slow-vehicle detector
M Merge detector (optional)

Figure 4.13. Layout of a gap-acceptance merge-control system

be warranted at locations where the geometrics are substandard and the primary concern is to improve the safety of the merging operation.

Integrated Ramp Control

Integrated ramp control refers to the application of ramp control to a series of entrance ramps where the interdependency of entrance ramp operations is taken into account. The primary objective of integrated ramp control is to prevent or reduce the occurrence of congestion on the freeway. Therefore, the control of each ramp in the control system is based on the demand-capacity considerations for the whole system rather than on the demand-capacity constraint at each individual ramp. This concept does not necessarily imply the use of large computer control systems since small subsystems may be coordinated by the use of mutual coordination of adjacent ramp meter controllers.

If congestion is to be prevented or reduced on the freeway system, the concept of integrated ramp control must be used in the design of a system of controls for a section of freeway with more than one entrance ramp. It is applied in the following types of systems:

- Integrated pretimed metering (including ramp closure)
- Traffic-responsive metering
- Gap-acceptance merge control

A discussion of integrated ramp control applied to each of these systems follows.

Integrated Pretimed Metering. Integrated pretimed metering refers to the application of pretimed metering to a series of entrance ramps. The metering rate for each of these ramps is determined in accordance with demand-capacity constraints at the other ramps as well as its own local demand-capacity constraint. These metering rates, which are computed from historical data pertaining to each control interval, require the following information:

- Mainline and entrance ramp demands
- Freeway capacities immediately downstream of each entrance ramp
- Description of the traffic pattern within the freeway section to be controlled

This information provides the basis for establishing the demand-capacity constraints of the entrance ramps and their interdependencies.

- Fundamental metering rate calculations — Given the required data, the fundamental procedure for computing metering rates involves five steps:

(1) Start with the entrance ramp which is farthest upstream.

(2) Determine the total demand (upstream mainline demand plus ramp demand) for the freeway section immediately downstream of the ramp.

(3) Compare the total demand to the capacity of the downstream section, and proceed as follows:

  (a) If the total demand is less than the capacity, metering is not required at this ramp by this demand-capacity constraint. Therefore, skip Step 4 and go immediately to Step 5.

  (b) If the total demand is greater than the capacity, metering is required at this ramp by the demand-capacity constraint. Therefore, proceed to Step 5.

(4) Compare the upstream mainline demand to the capacity of the downsteam section, and proceed as follows:

  (a) If the upstream mainline demand is less than the capacity, then the allowable entrance ramp volume (or metering rate) is set equal to the difference between the capacity and the upstream mainline demand.

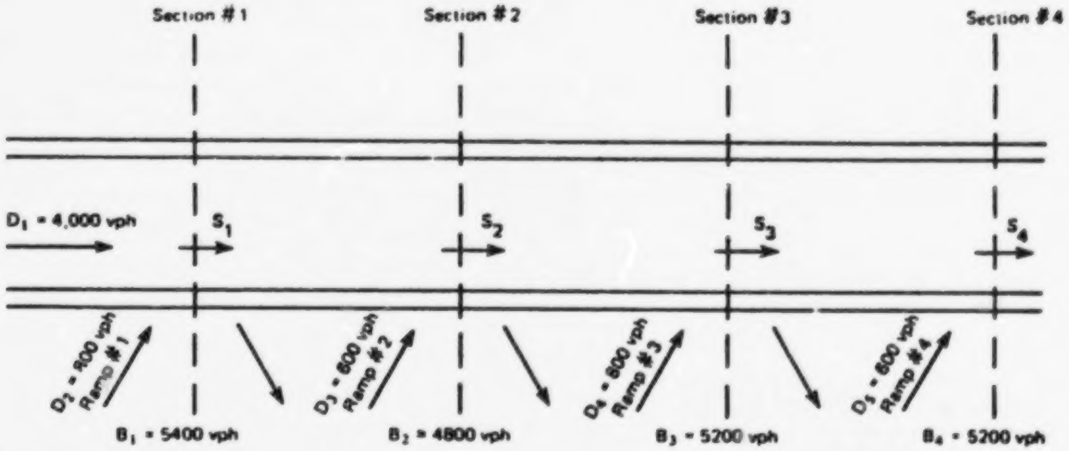
  (b) If the upstream mainline demand is greater than or equal to the capacity, then the allowable entrance ramp volume is zero, and the ramp must be closed. If the upstream mainline demand is greater than the capacity, the volumes permitted to enter at ramps upstream must be reduced accordingly.

  The total reduction in the allowable entrance ramp volumes upstream is equal to the difference between the upstream mainline demand and the capacity, adjusted to account for that portion of the traffic entering upstream that exits before it reaches the downstream entrance ramp being closed.

(5) Select the next entrance ramp downstream, and go back to Step 2.

This procedure is illustrated by the following examples.

- Example No. 1 — In the example case shown in Figure 4.14, pretimed metering rates are calculated for


Section # 1
Section # 2
Section #3
Section # 4
D₁ = 4,000 vph
S₁
S₂
S₃
S₄
D₂ = 800 vph
Ramp # 1
D₃ = 600 vph
Ramp # 2
D₄ = 800 vph
Ramp # 3
D₅ = 600 vph
Ramp # 4
B₁ = 5400 vph
B₂ = 4800 vph
B₃ = 5200 vph
B₄ = 5200 vph

X_i = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section #1

- Set $X_1 = D_1 = \underline{4000 \text{ vph}}$
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4000)+(1.00)(800) = 4800 \text{ vph} < B_1 = 5400 \text{ vph}; \therefore \underline{X_2 = 800 \text{ vph}}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4000)+(0.75)(800)+(1.00)(600) = 5000 \text{ vph} > B_2 = 4800 \text{ vph}; \therefore \underline{X_3 = 400 \text{ vph}}$
- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4000)+(0.70)(800)+(0.90)(400) + (1.00)(800) = 5320 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore \underline{X_4 = 680 \text{ vph}}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4000) +(0.60)(800) +(0.85)(400) + (0.90)(680) + (1.00)(600) = 5432 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore \underline{X_5 = 368 \text{ vph}}$

Conclusion:

- Ramp # 1: No control needed.
- Ramp # 2: Meter at a rate of 400 vph.
- Ramp # 3: Meter at a rate of 680 vph.
- Ramp # 4: Meter at a rate of 368 vph.

Figure 4.14. Integrated entrance ramp control: Example No. 1 — Calculation of pretimed metering rates

an integrated, pretimed control system comprised of four entrance ramps. In a review of this example, the following points should be noted:

- Since only entrance ramp control is being considered and not mainline control, the allowable mainline volume at Section 1, X_1 is set equal to the mainline demand D_1.
- With the notation given in Figure 4.14, the demand, S_j, at a Section, j, is computed by the following equation:

$$S_j = \left(\sum_{i=1}^{j} A_{ij} X_i \right) + A_{j+1,j} D_{j+1} \qquad (4.1)$$

Where:

X_i = Allowable volume at Input i
D_i = Demand at Input i
A_{ij} = Decimal fraction of vehicles entering at Input i which pass through Section j
S_j = Demand at Section j

As it happens, the metering rate computed for each entrance ramp in this particular example is determined solely by the demand-capacity constraint at the section immediately downstream and is not influenced by the demand-capacity constraints at other ramps.

- Example No. 2 — The data given in the example shown in Figure 4.15 are the same as that given in the previous example, except that the mainline demand, D_1, is 4,600 vph instead of 4,000 vph. In this case, the metering rates at Ramps 2, 3, and 4 are determined solely by their respective downstream demand-capacity constraints, as was the case in the previous example. However, the metering rate at Ramp 1, rather than being determined by the demand-capacity constraint at Section 1, is established in accordance with the demand-capacity constraint at Ramp 2, as is described below.

The demand, S_2, at Section 2 is 5,570 vph, which is 770 vph greater than the capacity, B_2, at Section 2 (4,800 vph). If Ramp 2 is closed, the demand at Section 2 is reduced to 4,970 vph, a volume which also exceeds the capacity, B_2. Therefore, it is necessary to reduce the allowable volume, X_2, entering at Ramp 1 (Input 2). The allowable volume, X_2, must be reduced enough to reduce the demand, S_2, by 170 vph. The amount of the reduction is equal to the 170 vph divided by the decimal fraction, A_{22}, of the vehicles entering at Ramp 1 and passing through Section 2 (170 vph/0.75 = 227 vph). Therefore, the allowable volume, X_2, at Ramp 1 would be 573 vph instead of 800 vph.

In this procedure, excess demand, $S_j - B_j$, at any section, j, is removed by reducing the allowable volume on the entrance ramp immediately upstream. If, instead, the allowable volumes on entrance ramp farther upstream were reduced, a large number of vehicles would have to be removed from these ramps in order to reduce the demand, S_j, sufficiently at any section, j. This is necessary because some of the vehicles that enter at these ramps will exit the freeway before they reach Section j.

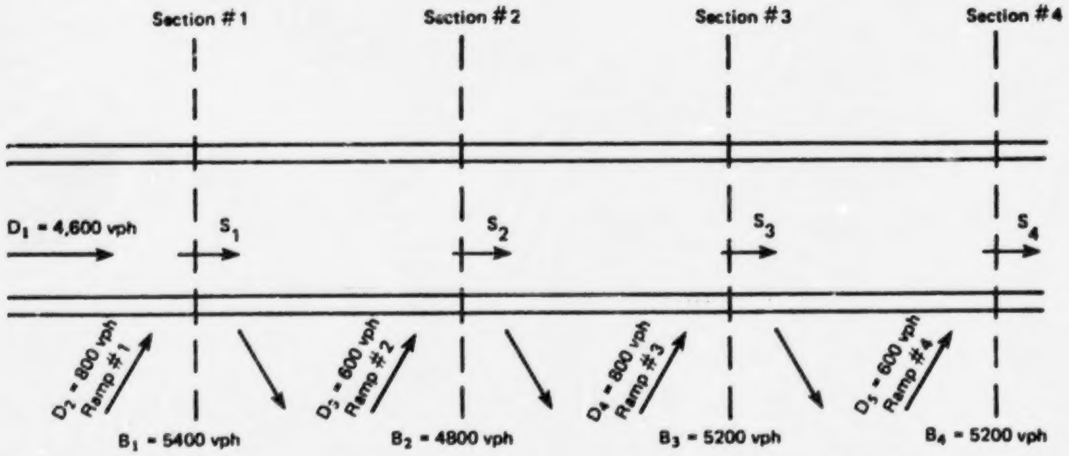
- Example No. 3 — Again, in the situation presented in Figure 4.14, allowable ramp volumes would be calculated as follows. If the excess demand (200 vph) at Section 2 were to be removed by reducing the allowable volume, X_2, at Ramp 1, the volume at Ramp 1 would have to be reduced by 267 vph. Consequently, the allowable entrance ramp volumes would be as follows:

Ramp No.		Volume (vph)
Ramp	1	533
Ramp	2	600
Ramp	3	687
Ramp	4	352
Total input		2,172

The total input of 2,172 vph, however, is less than that of 2,248 vph, the volume which is obtained if Ramp 2 is metered as in Example 1. Thus, the fundamental approach described will result in the optimal utilization of the freeway. It maximizes the sum of the allowable entrance ramp volumes, a procedure which corresponds to maximizing system output for steady-state, noncongested flow conditions (*35*). The total travel in the system is also maximized (*36*).

Linear Programming Formulation — The fundamental procedure described in Examples 1 and 2 can be formulated as a linear programming model (*35*). This model may be used to compute optimal allowable entrance ramp volumes. In terms of the notation defined in Figures 4.14 and 4.15, the linear programming model would be as follows:

- Maximize ΣX_i, where n is the number of inputs
- Subject to the following constraints:
  - Demand capacity:


Section #1
Section #2
Section #3
Section #4
D₁ = 4,600 vph
S₁
S₂
S₃
S₄
D₂ = 800 vph Ramp #1
D₃ = 600 vph Ramp #2
D₄ = 800 vph Ramp #3
D₅ = 600 vph Ramp #4
B₁ = 5400 vph
B₂ = 4800 vph
B₃ = 5200 vph
B₄ = 5200 vph

X_i = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section #1

- Set $X_1 = D_1 = \underline{4600 \text{ vph}}$
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4600)+(1.00)(800) = 5400 \text{ vph} = B_1 = 5400 \text{ vph}; \therefore \underline{X_2 = 800 \text{ vph}}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4600)+(0.75)(800)+(1.00)(600) = 5570 \text{ vph} > B_2 = 4800 \text{ vph};$

  $\therefore \underline{X_3 = 0}$ and volume entering upstream must be reduced by 170 vph;
  $\therefore X_2 = 800 - 170/A_{22} = 800 - 170/0.75 = \underline{573 \text{ vph}}$
- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4600)+(0.70)(573)+(0.90)(0) + (1.00)(800) = 5341 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore \underline{X_4 = 659 \text{ vph}}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4600) +(0.60)(573) +(0.85)(0) + (0.90)(659) + (1.00)(600) = 5447 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore \underline{X_5 = 353 \text{ vph}}$

Conclusion:

- Ramp #1: Meter at a rate of 573 vph.
- Ramp #2: Close.
- Ramp #3: Meter at a rate of 659 vph.
- Ramp #4: Meter at a rate of 353 vph.

Figure 4.15. Integrated entrance ramp control: Example No. 2 — Calculation of pretimed metering rates

$$\sum_{i=1}^{n} A_{ij}X_i \leq B_j; \quad j = 1,\ldots, n-1 \qquad (4.2)$$

- At Section 1, allowable mainline volume ≤ mainline demand:

$$X_1 = D_1 \qquad (4.3)$$

- Allowable entrance ramp volume ≥ entrance ramp demand:

$$X_i \leq D_i; \; i = 2,\ldots,n \qquad (4.4)$$

- Allowable entrance ramp volume equals minimum allowable ramp volume:

$$X_i \geq \min x_i \geq 0; \; i = 2,\ldots,n \qquad (4.5)$$

The use of the linear programming model yields allowable entrance ramp volumes which are identical to those obtained by using the fundamental procedure described above.

Practical Considerations — The allowable entrance ramp volumes (or metering rates) calculated for an integrated ramp control system should be evaluated with respect to the following practical considerations:

- Metering rates of less than 180 to 240 vph (3 to 4 vpm) are not feasible because drivers required to wait longer than 15 to 20 sec at a ramp metering signal often believe that the signal is not working correctly. They will, therefore, proceed on a red indication by the signal. Thus, if a metering rate of less than 180 to 240 vph is calculated, consideration should be given either to closing the ramp or to metering it at a higher rate.
- Practical maximum metering rates are about 900 vph for single-entry metering and approximately 1,100 vph for platoon metering. Therefore, for a metering rate greater than the maximum for the metering type to be used, it should be set less than or equal to the practical maximum rate, and the metering rates at the other entrance ramps should be adjusted accordingly.
- Metering rates at each entrance ramp should be evaluated with regard to available storage at the ramp and potential resulting congestion on the adjoining surface street system. If the storage is not sufficient, it may be necessary either to close the ramp or to increase the metering rate.
- Metering rates equal to zero indicate that an entrance ramp closure is necessary. However, the closure of a particular entrance ramp may not be acceptable. Therefore, it may be necessary to increase a zero metering rate to some minimum acceptable rate.
- The procedure described for computing metering rates gives preference to traffic entering the system near the upstream end. Consequently, metering rates at entrance ramps downstream may be too restrictive to be acceptable to the motoring public. Therefore, it may be necessary to increase the metering rates computed for some of the downstream entrance ramps, and thus to reduce accordingly the metering rates for some of the upstream entrance ramps.

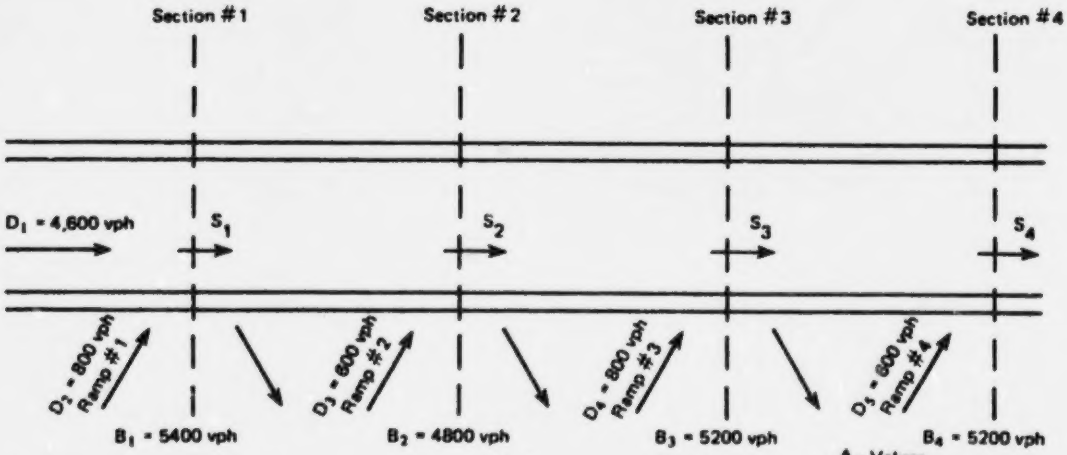
If any of the computed metering rates were to be altered because of one or more of the practical considerations mentioned above, the metering rates at the other entrance ramps would have to be adjusted accordingly to ensure both an optimal utilization of the freeway and a noncongested flow.

- Example No. 4 — If it were necessary to maintain a metering rate of at least 240 vph at Ramp 2 in the example presented in Figure 4.15, it would be necessary to follow the adjustment procedure for the metering rates at the other entrance ramps (as shown in Figure 4.16). The allowable volume, X_2 (573 vph), at Ramp 1 would have to be reduced by 320 vph in order to allow 240 vph to enter at Ramp 2 and still satisfy the demand-capacity constraint at Section 2. This reduction also decreases the mainline demand at Sections 3 and 4. Thus, the allowable volumes at Ramps 3 and 4 are increased to maximize the utilization of the freeway at these sections.

It is usually difficult to obtain reliable estimates of the A_{ij} values, because these vary with time and generally exhibit a high variance. Also, the O/D type studies used to collect these data are expensive and do not provide real-time data.

Integrated Traffic-Responsive Metering. Integrated traffic-responsive metering is the application of traffic-responsive metering to a series of entrance ramps where the metering rates at each ramp are selected in accordance with system, as well as local, demand-capacity constraints.

- System operation — During each control interval, real-time measurements are taken of traffic variables (usually volume, occupancy, and/or speed). The data are used to define the demand-capacity conditions at


Section #1
Section #2
Section #3
Section #4
D₁ = 4,600 vph
S₁
S₂
S₃
S₄
D₂ = 800 vph
Ramp #1
D₃ = 600 vph
Ramp #2
D₄ = 800 vph
Ramp #3
D₅ = 600 vph
Ramp #4
B₁ = 5400 vph
B₂ = 4800 vph
B₃ = 5200 vph
B₄ = 5200 vph

X_j = allowable volume at input *j*

D_j = demand at input *j*

B_j = capacity at section *j*

A_{ij} = decimal fraction of vehicles entering at input *i* which pass through section *j*

S_j = demand at section j

A_{ij} Values

j *i*	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_j's starting at section #1

- Set $X_1 = D_1 = \underline{4600 \text{ vph}}$
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4600)+(1.00)(800) = 5400 \text{ vph} = B_1 = 5400 \text{ vph}; \therefore \underline{X_2 = 800 \text{ vph}}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4600)+(0.75)(800)+(1.00)(600) = 5570 \text{ vph} > B_2 = 4800 \text{ vph};$

  Since X_3 must equal at least 240 vph; $\underline{X_3 = 240 \text{ vph}}$ and volume entering upstream must be reduced by 410 vph;
  $\therefore X_2 = 800 - 410/A_{22} = 800 - 410/0.75 = \underline{253 \text{ vph}}$
- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4600)+(0.70)(253)+(0.90)(240) + (1.00)(800) = 5333 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore \underline{X_4 = 667 \text{ vph}}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4600) + (0.60)(253) + (0.85)(240) + (0.90)(667) + (1.00)(600) = 5466 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore \underline{X_5 = 334 \text{ vph}}$

Conclusion:

- **Ramp #1:** Meter at a rate of 253 vph.
- **Ramp #2 :** Meter at a rate of 240 vph.
- **Ramp #3:** Meter at a rate of 667 vph.
- **Ramp #4:** Meter at a rate of 334 vph.

Figure 4.16. Integrated entrance ramp control: Example No. 4 — Calculation of pretimed metering rates

each entrance ramp. Then, on the basis of these measurements, both an independent and an integrated metering rate are calculated for each entrance ramp. Of these two metering rates, the one that is the more restrictive is selected to be used during the next successive control interval.

- Metering rates — The methods used to calculate independent and integrated traffic-responsive metering rates are basically the same as those used to compute independent and integrated, pretimed metering rates. Usually, instead of metering rates being calculated in real time, a set is precomputed for the range of demand-capacity conditions expected, from which the metering rates are then selected in real time. The linear programming model is often used to calculate predetermined sets of integrated, traffic-responsive metering rates. Also, the metering rates are usually subject to the merge-detector, queue-detector, and maximum-red-time overrides used in traffic-responsive metering.

Integrated Gap-Acceptance Merge Control. Integrated, gap-acceptance merge control is the application of gap-acceptance merge control to a series of entrance ramps where such control at the individual ramps is subject to system demand-capacity constraints.

Metering rates are computed by the procedure described for calculating integrated, pretimed metering rates. These integrated metering rates are computed for each entrance ramp on the basis of the real-time measurements of traffic variables which are used to define the system's demand-capacity conditions. Then, for each entrance ramp, a minimum acceptable gap setting is determined which will yield a ramp volume corresponding to the integrated metering rate. The minimum acceptable gap is the smallest gap in freeway mainlane traffic into which a ramp vehicle will merge. Larger settings of a minimum acceptable gap have the impact of reducing the metering rate.

Integrated vs. Independent Ramp Control. Comparisons of integrated and independent entrance ramp control indicate that increased benefits are realized with integrated ramp control (*37, 38*). Improvements occur in terms of the following:

- Lower travel time
- Higher total travel
- Fewer accidents

In addition, in the case of traffic-responsive metering, the greater system flexibility provided by integrated ramp control enables an optimal system response to individual variations in traffic demands and capacities resulting from incidents on the freeways.

Controller Interconnection. A significant feature of integrated ramp control is the interconnection among local ramp controllers which permits conditions at one location to affect the metering rate imposed at one or more other locations. Real-time metering plans are computed and updated by a central master controller, which issues metering rates to the respective local ramp controllers, based on freeway traffic information obtained from vehicle detectors throughout the system.

Figure 4.17 depicts a schematic representation of an integrated entrance ramp control system. The freeway is divided into sections, with each section containing one entrance ramp. Although the decision-making capabilities are centralized within the master controller, the processing of control intelligence may be distributed among the individual entrance ramps. For economic (and possibly reliability) reasons, there is a trend for decentralized decision-making, distributed computation, and hierarchical control (*39*).

A discussion of decentralized control of integrated ramp metering systems is provided by Loose, et al. (*39*).

Incremental Benefits of Different Levels of Control

As discussed earlier, the benefits offered by pretimed metering (including ramp closure) versus no access control include increased mainline speeds (reduced travel time), higher service volumes, less delay, safer merging operations, and reduced user costs. Beyond pretimed metering, the incremental benefits gained from traffic-responsive metering (local or systemwide) depend on the following factors (*40*):

- Variations in the ratio of mainline to entrance ramp demand — As mainline demand approaches capacity, the permissible metering rates become more and more constrained. On the other hand, as the mainline demand decreases, more traffic can be allowed onto the freeway from entrance ramps, and ramp metering control can exert greater impact on the quality of freeway flow, thus producing greater benefits.

  A measure of how much traffic-responsive control can vary the metering rates is called the controllability index, which is defined by the following formulation (*40*):

$$\text{Controllability Index} = \frac{I_{pc} - I_{min}}{I_{min}} \qquad (4.6)$$

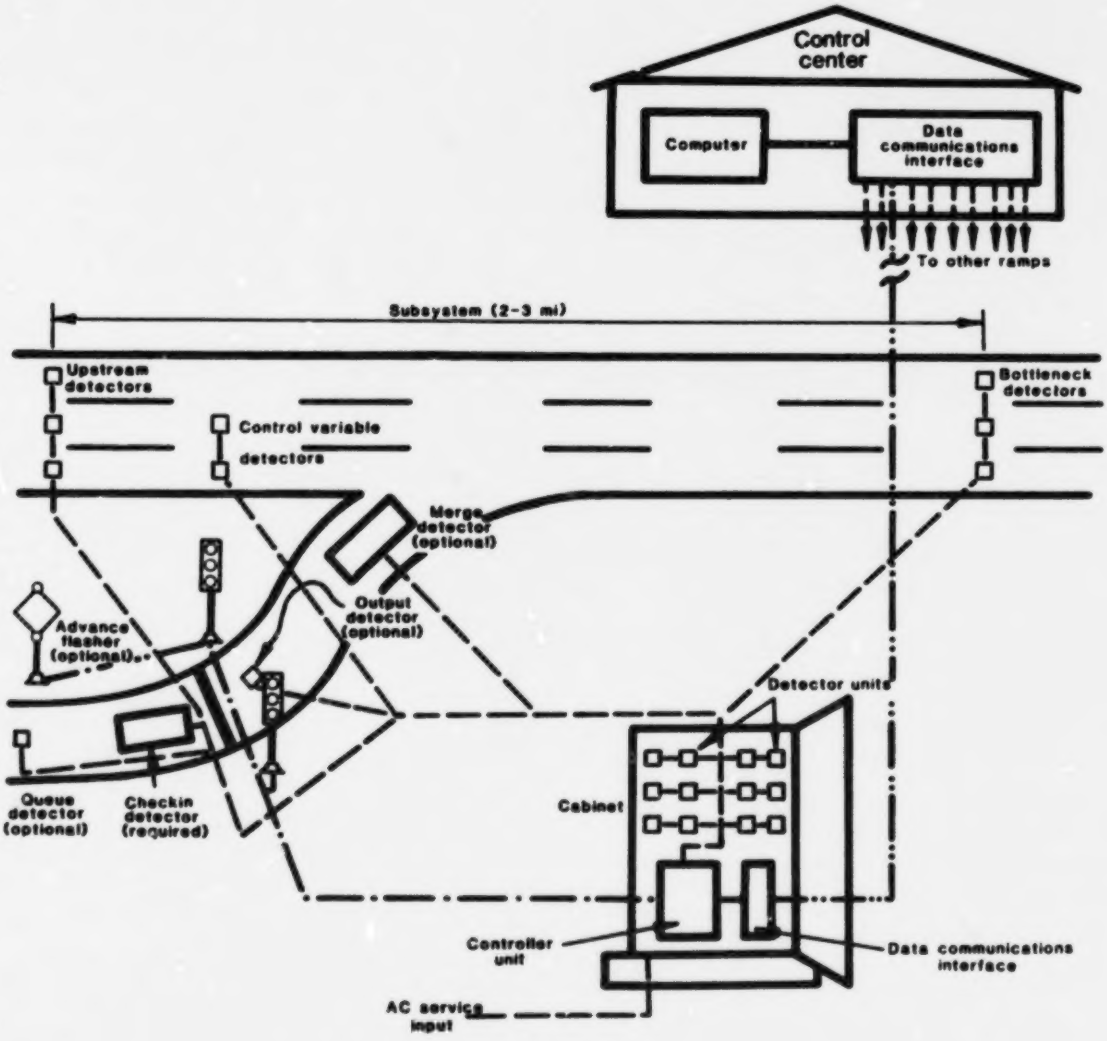

Control center
Computer
Data communications interface
To other ramps
Subsystem (2-3 mi)
Upstream detectors
Control variable detectors
Bottleneck detectors
Merge detector (optional)
Output detector (optional)
Advance flasher (optional)
Detector units
Cabinet
Queue detector (optional)
Checkin detector (required)
Controller unit
Data communications interface
AC service input

Figure 4.17. Schematic representation of integrated entrance ramp control system

Where:

I_{pc} = Total metered input with pretimed control
I_{min} = Total metered input when minimum metering rates are used

- Variations in overall traffic demand pattern — Traffic demand on the freeway and entrance ramps exhibit two types of variations: (1) shift in demand level, and (2) short-term fluctuations. The larger the magnitude of these types of demand variation, the higher the potential for benefits from traffic-responsive metering.
- Mainline capacity reductions — Reductions in mainline freeway capacity result from accidents, traffic incidents, and adverse weather conditions. As the frequency and impact of these capacity-reducing factors increase, more need is developed for traffic-responsive metering to cope with the variations in available capacity.

To determine the appropriate level of ramp metering control for a given freeway, the incremental benefits produced by local and systemwide traffic-responsive metering (relative to a base of pretimed metering) must be estimated. Computer simulation can be effectively used in evaluating control benefits. In addition, the incremental system costs (installation, operation, maintenance) and the incremental user costs (travel time, vehicle operating costs, accidents, air pollution emission) must be estimated. Incremental benefits and incremental costs can then be used to conduct a benefit/cost or utility/cost analysis to decide upon the most desirable type of ramp metering. A discussion of utility/cost analysis is provided in Chapter 10.

The growth in traffic demand over the lifetime of a ramp metering project may reduce the incremental benefits of a traffic-responsive type of ramp metering control (local or systemwide). To help explain, Figure 4.18 shows the general relationship between the controllability index and incremental travel-time savings. As traffic demand grows substantially over the lifetime of the project, the controllability index of the freeway decreases. Since the benefits are nonlinearly related to the controllability, it is possible that the benefits could decrease faster than the growth rate in demand. In planning ramp metering installations, the engineer should be aware of this effect. It is recommended that the analysis be repeated for as many years as are in the expected project-life duration.

The incremental benefits analysis is but one component of a system selection process which, in turn, is a component of a freeway traffic management decision process. The major components of this decision process include the following:

- Developing a basic analysis of freeway operations
- Making a detailed analysis of freeway operations and determining improvement alternatives
- Examining the feasibility of ramp control as an improvement alternative
- Analyzing the site conditions and selecting the control level

A detailed discussion of the incremental benefits of different types of ramp metering control is provided in NCHRP Report 232 (*40*).

4.3 EXIT RAMP CONTROL

Exit ramp control is seldom used as a means of freeway traffic control because the opportunities for its effective application are limited. In many situations, the use of exit ramp control would actually be contrary to the objective of safe and efficient freeway operations. Also, it should only be used where destinations can easily be reached by using alternate exits.

Exit ramp closure can be used effectively to reduce safety hazards and congestion caused by excessive weaving between closely spaced ramps and long queues on exit ramps. Also, exit ramp closure can be used at a lane drop location by closing downstream exit ramps in order to encourage more traffic to leave the freeway at the exit ramps before the lane drop and thus decrease the demand on the freeway section beyond the lane drop. However, as in the case of entrance ramp closure, exit ramp closure might not be acceptable because of the increased travel it creates for some motorists.

4.4 MAINLINE CONTROL

Another approach gaining acceptance is the use of controls for traffic on the freeway mainline itself. Mainline control then is concerned with the regulation, warning, and guidance of traffic on the main freeway lanes in order to achieve the following:

- Improve the uniformity and stability of traffic flow and forestall congestion
- Reduce the potential for rear-end collisions if congestion does develop
- Facilitate incident management and recovery from congestion
- Divert freeway traffic to alternate routes in order to make better use of corridor capacity
- Change the directional capacity of the freeway by using reversible lanes

The application of mainline control to freeways in the United States generally has been limited to selected experiments and research efforts, although considerable interest is being expressed in the concept. This interest is generated by the positive results experienced by extensive application of various mainline control strategies in West Germany, Japan, and the United Kingdom. Mainline control is typically implemented through one or more of the following means:

- Driver information systems
- Variable-speed control
- Lane closure
- Mainline metering
- Reversible lane control

Driver Information Systems

Driver information systems, as a form of mainline control, are used primarily to advise motorists of freeway conditions ahead. They are designed to provide meaningful, real-time information that will enable motorists to drive more safely and divert to alternative routes if necessary.

To be effective, driver information systems must be designed to provide the type of information needed by the motorists. In a study of driver information needs (*41*), the following principles for the presentation of driver information were identified:

- Observe primacy, giving the more important information more impact
- Prevent overloading of information, or its effectiveness is lost
- Give information well in advance
- Spread information out to prevent driver boredom
- Avoid unexpected information

Another evaluation of real-time visual information displays (*42*) has determined that drivers prefer real-time information sign displays that are simple and of a unique design that can distinguish them from other types of freeway signing. It was also concluded that drivers preferred visual displays that provided clear distinction between normal and abnormal traffic conditions.

The driver information systems most deployed in mainline control are single- and variable-message signing, lane-control signals, and roadside and commercial radio broadcasts. Detailed descriptions of each are presented in Chapter 9.

Variable-Speed Control

Advisory variable-speed control may be used to reduce the speed of traffic on a freeway to a level that corresponds to the maximum volume of traffic flow. As illustrated in Figure 4.10, the fundamental volume-speed density relationships, based on the assumption of uniform traffic flow, define an optimum speed and an optimum density at maximum volume. Therefore, as the number of vehicles on a freeway increases to optimum density, a variable-speed system may improve the stability of traffic flow and help to ensure that the maximum volume is achieved. Of course, if the demand is not limited to less than capacity, variable-speed control can only, at best, postpone the occurrence of congestion. But, by improving the uniformity of traffic speeds on the freeway and sufficiently reducing them during peak-flow conditions, variable-speed control should at least reduce

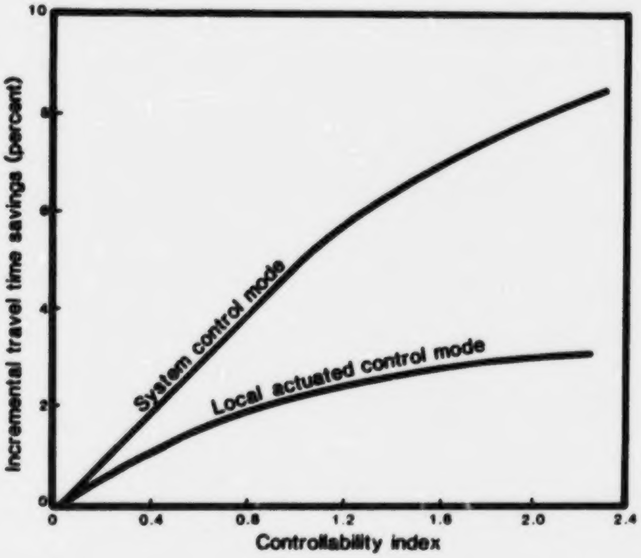


Figure 4.18. Relationship between the controllability index and incremental travel-time savings

Source: Reference (*40*)

126

the occurrence of rear-end collisions as congestion develops.

Variable-speed control may also be used during off-peak periods as an advance warning system to prevent accidents. Speed limits are established ahead of the scenes of accidents and traffic obstruction in order to slow traffic and alert drivers to the existence of a traffic hazard ahead. In addition, lower speed limits could be imposed in the case of hazardous driving conditions such as fog or icy or slippery pavements.

Lane Closure

Lane closure prohibits entry to one or more of the mainlanes on the freeway. It is used to increase the efficiency and safety of freeway operations during periods of reduced capacity. Use of closure as a means of mainline control is usually confined to the following applications:

- Advance warning of lane blockage
- Improvement of entrance ramp merging operations
- Traffic diversion
- Tunnel control

A brief discussion of some examples of these applications is presented in the sections which follow.

Warning of Lane Blockage. In Detroit, lane-control signs were used to indicate the existence of temporary lane blockages downstream caused by maintenance operations. A typical installation is shown in Figure 4.19. The effectiveness of this system seemed to depend on the freeway demand (*43*). If the demand was less than the capacity remaining, the vehicles appeared to observe the red X indication and to leave the closed lane farther in advance of the blockage then if no lane-control signs were used, thereby easing flow through the bottleneck. However, if the demand was greater than the capacity remaining, though there was some earlier movement out of the blocked lane, no corresponding increase occurred in the volume of traffic flow through the bottleneck. The usefulness of the system thus seemed to be limited to off-peak periods. The effectiveness of this system with respect to a reduction in accidents because drivers had been alerted to blocked lanes downstream was not evaluated. Because of its limited effectiveness, the operation of the system was not continued.

In Austin, Texas, lane control signals and changeable message signs are used on a freeway where express elevated mainlanes are introduced parallel to and above existing mainlanes. Tests of the system conducted during off-peak periods proved it to be extremely effective in shifting vehicles to the appropriate open lanes (*44*).

In the Netherlands, lane-control signals are used in conjunction with variable-speed control messages to warn drivers of lane blockages ahead (*45*). Fiber-optic-type matrix signals are located above each lane at intervals of about 500 meters. Each signal has the ability to display a range of numerical speed messages, a red X, a right or left change lane arrow, and an end of temporary limits message. Mainline detectors spaced at 500-meter intervals provide data for incident detection. If warranted by an incident, the system can be used to stop all traffic on the mainline. The system has been found to be effective in reducing the frequency and severity of accidents on motorways.

Improvement of Entrance Ramp Merging Operations. In Houston, lane closure has been used to reduce congestion caused by merging operations during heavy traffic flow conditions at a freeway-to-freeway interchange. The problem is caused by a 2-lane entrance ramp merging with a 3-lane mainline section into a 4-lane mainline section. A layout of this location is shown in Figure 4.20. Prior to the installation of the lane-closure system, the queue of traffic on the ramp waiting to merge would extend back onto the other freeway, because of the difficulty of the merging operation. The solution was to close the right lane on the 3-lane section during peak periods. Lane-control signals have been used instead of the traffic cones shown in Figure 4.20. Lane-control signals, shown in Figure 4.21, were installed upstream of the merge area, and loop detectors were installed on the entrance ramp. When a queue is detected on the ramp, the lane-control sign displays a red X over the right lane, indicating the lane is closed. When there is not a queue detected on the ramp, a green arrow is displayed over the lane. While the lane control signals provided flexibility to open or close the lane in response to traffic demands, it was found that effective enforcement was necessary to ensure compliance. The system has now been evolved to a permanent blockage of the right lane.

Traffic Diversion. In Germany, for traffic approaching Munich, lane closure is used in a signal system to divert flow from the mainline to alternate routes during peak periods (*46*). A layout of the system is shown in Figure 4.22. The system includes (1) 5 flashing yellow lights on a signal bridge spanning the roadway, (2) conventional red-yellow-green traffic signals on a second bridge downstream of the first one, and finally (3) detour signs. After having been stopped, the vehicles are directed to leave the mainline to the alternate routes via the exit ramp.

Tunnel Control. Lane closure is often used in tunnel control on the mainline. For example, in the Naples, Italy, system (*47*), if an incident or very slow traffic is detected in a tunnel by speed and occupancy checks, entrance to the tunnel is denied by conventional, red-yellow-green traffic signals. Similar techniques are being used in several United States installations, including Minneapolis and the Port Authority of New York and New Jersey in the Lincoln Tunnel.

Mainline Metering

Although metering has not yet attained widespread acceptance as a concept of freeway mainline control, it has been used since the late 1950s to improve traffic flow through tunnels. It has also been successfully used in other special freeway situations for approaches to bridges and for control of mainline-to-mainline connectors.

Situations where traffic demand exceeds corridor capacity may offer additional opportunities for mainline metering. In such situations, congestion on the freeway cannot be prevented by entrance ramp control, and stop-and-go traffic flow occurs. Therefore, it may be desirable to install mainline metering on the mainline approach to the entrance-ramp-control section of the freeway. Although it would create congestion on the mainline upstream, noncongested flow could be maintained on the mainline downstream through the control section. Also, higher volumes could be allowed to enter the freeway on the entrance ramps downstream, which might enable a more publicly acceptable allocation of freeway capacity among the different traffic demands along the freeway.

In Japan, in Osaka and Tokyo, the effect of mainline metering has been achieved by closing toll booths on the mainlines of the expressways. By regulating the number of toll booths that are open at any given time, the traffic demand entering the expressway system via the mainline is controlled according to available expressway demand and capacity downstream.

Another application of mainline metering is the computerized toll plaza traffic-signal system which has been installed on the east end of the San Francisco - Oakland Bay Bridge. Traffic signals are placed over each of the 14 nonpriority westbound lanes at a point downstream of the toll booths and release vehicles to merge into 5 lanes on the bridge.

Freeway-to-freeway connector metering has been implemented in San Diego and Minneapolis (*48*). In San Diego, three interchanges have been treated with connector

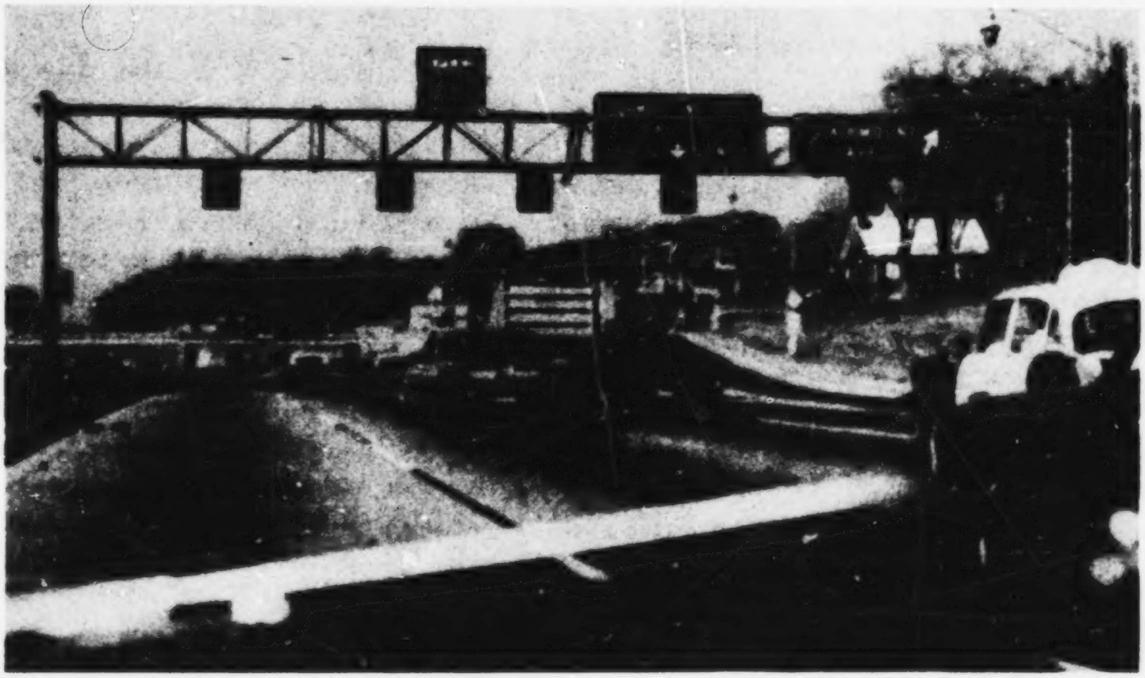


Figure 4.19. Variable-speed and lane controls tested in Detroit (Michigan)

Source: Reference (*27*)

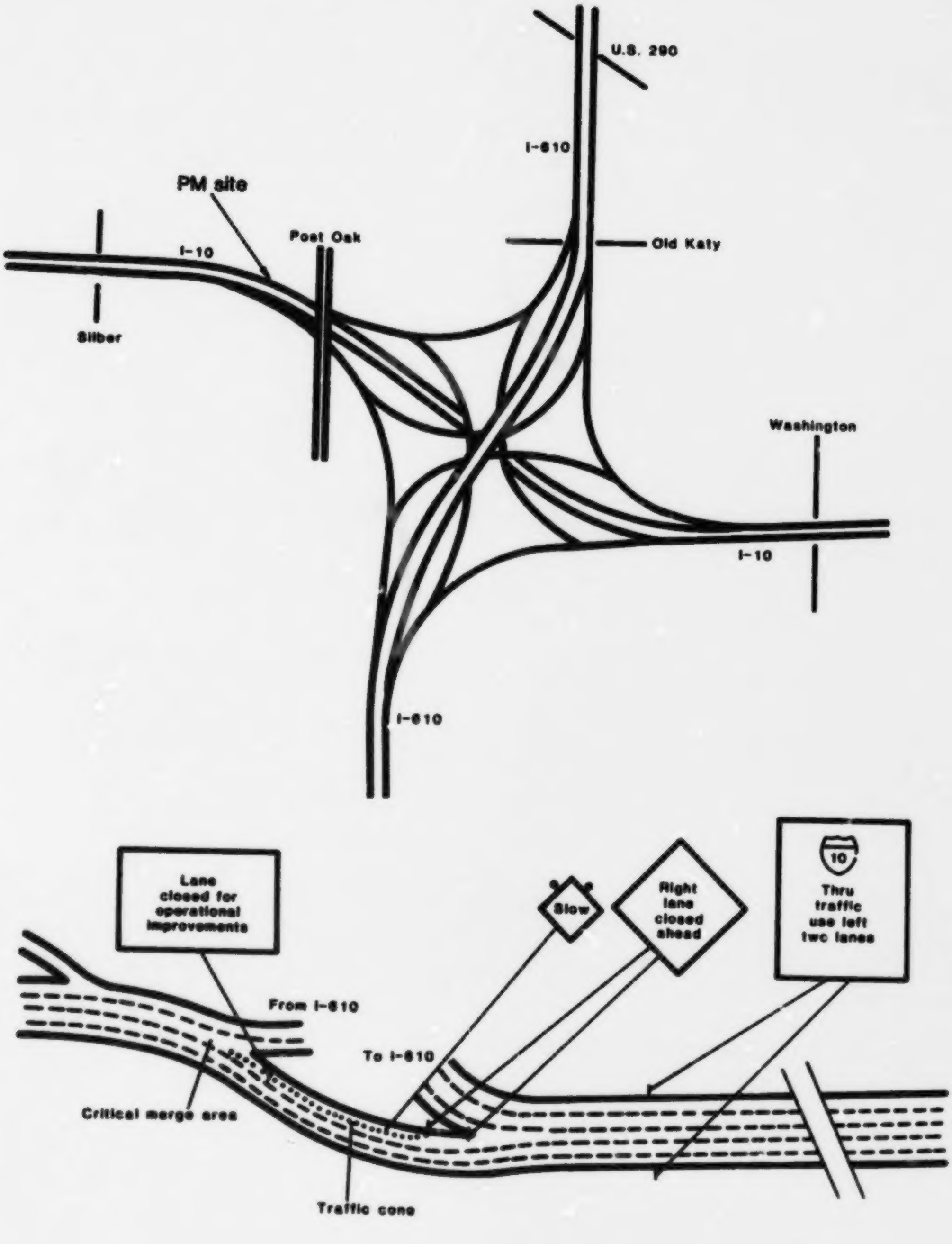

U.S. 290
I-610
PM site
Post Oak
I-10
Old Katy
Silber
Washington
I-10
I-610
Lane closed for operational improvements
Slow
Right lane closed ahead
10
Thru traffic use left two lanes
From I-610
To I-610
Critical merge area
Traffic cone

Figure 4.20. Mainline lane-closure control at freeway-to-freeway interchange in Houston (Texas)

Source: Reference (*27*)

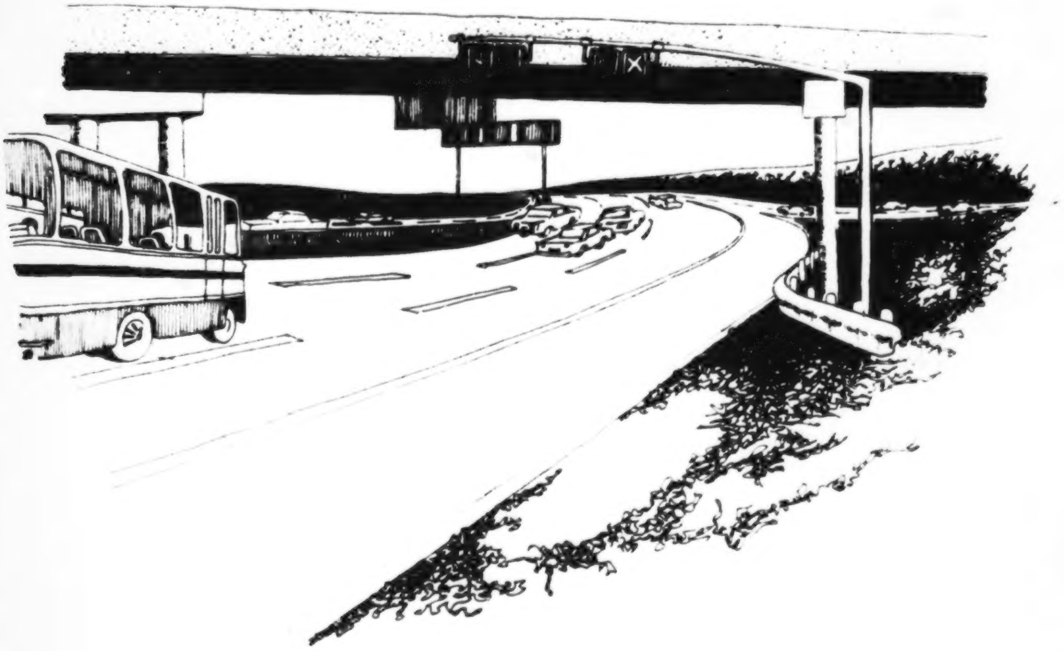


Figure 4.21. Lane-control signal used for mainline lane closure control at freeway-to-freeway interchange in Houston (Texas)

metering installations on the Route 94 freeway. Figure 4.23 shows the connector metering installation at the three-level interchange connecting Route 94 and I-805. In Minneapolis, connector metering has been implemented at 2 interchanges of the I-35W freeway. Demand on metered connectors is high, and it forms a large fraction of the total demand at point of entry to the freeway. In most instances, if a connection was not metered, congestion on the freeway would result (*48*).

Reversible Lane Control

Reversible lanes are used to change the directional capacity of a freeway in order to accommodate peak directional traffic demands. Therefore, if reversible lanes are to be warranted, peak-period traffic volumes must exhibit a significant directional imbalance (e.g., 70 percent, 30 percent) which would be predicted to continue to exist for a number of years in the future. If warranted, reversible lanes would enable a more economical and efficient use of road space and right-of-way.

The concept of reversible lanes also has been incorporated into the design of some freeways (e.g., Kennedy Expressway in Chicago and Interstate 5 in Seattle, Washington).

The Kennedy Expressway in Chicago has a 7-mi, 2-lane reversible roadway built in the median strip. The reversible lanes are express lanes and have only one access point between their terminals for outbound-only flow. The outer roadways have 3 to 4 lanes and operate in only one direction.

Interstate 5 on the northern approach to Seattle has a 7.5-mi. reversible-lane section in the median. However, here the reversible lanes are not express lanes and have several interchange points. The major features of this system are discussed below (*27*):

- The only transfer points between the reversible-lane section and the outer roadways are at the 2 ends of the section. The other 7 interchanges are direct transfers between the reversible lanes and the arterial street system.
- The ramp connections to the reversible roadway are controlled by devices that include (1) horizontal shear gates, (2) vertical-lift gates, and (3) changeable-message signs to inform the motorist in which direction the roadway is operating. These devices can be activated either locally at each ramp site, or remotely from a central control office adjacent to the freeway.

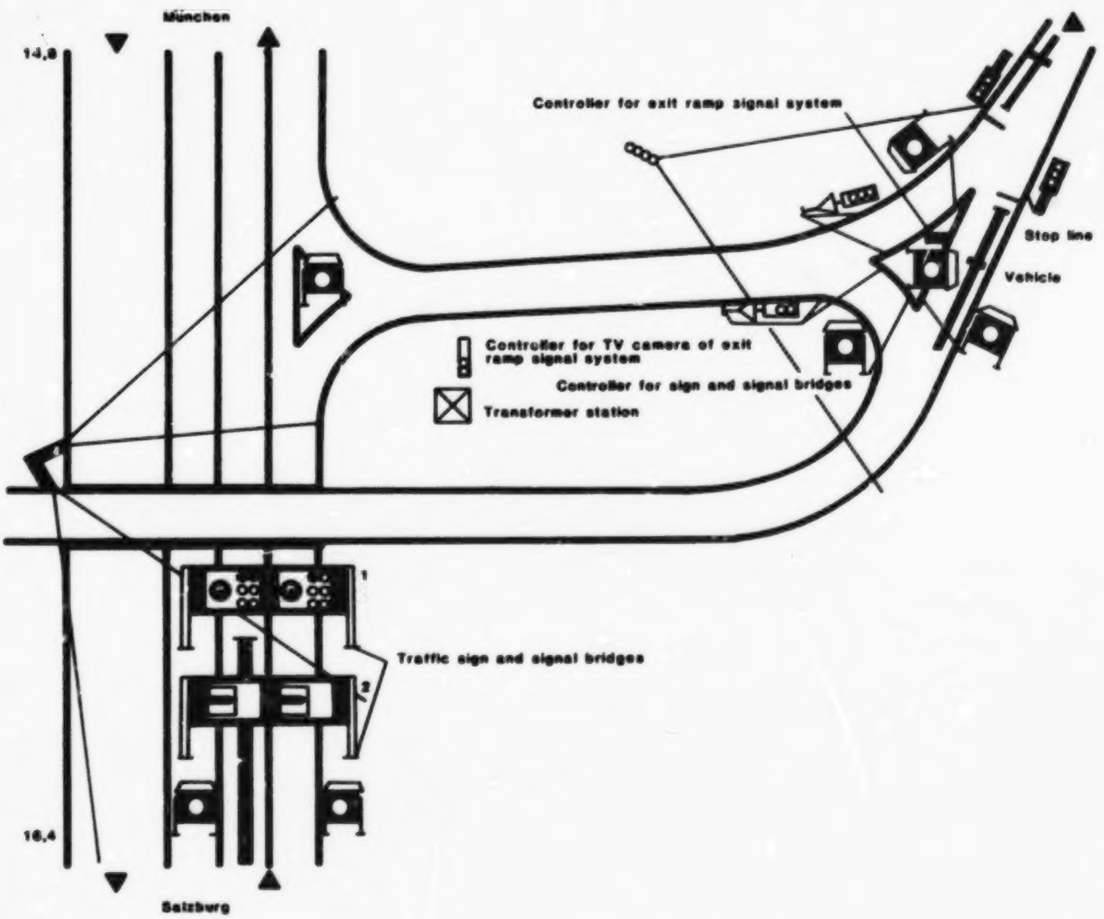

München
14,8
Controller for exit ramp signal system
Stop line
Vehicle
Controller for TV camera of exit ramp signal system
Controller for sign and signal bridges
Transformer station
1
Traffic sign and signal bridges
2
16,4
Salzburg

Figure 4.22. Mainlane lane closure used in traffic diversion system in Germany

Source: Reference (*45*)

- Closed circuit television initially used to monitor ramp sites during any remote activation of traffic control devices has been discontinued in favor of on-site manual changes which permit visual inspection for stalled vehicles, etc.

- Lane reversal is performed at the same times 7 days a week to allow motorists to become familiar with the system.

4.5 CORRIDOR CONTROL AND SURVEILLANCE

Objective

The purpose of corridor control is to attain full utilization of all available facilities in the freeway corridor. A freeway corridor, then, contains the freeway and its ramps, frontage roads (if they exist), parallel arterial streets that can be used as alternate routes, and cross streets that are links between the freeway ramps and

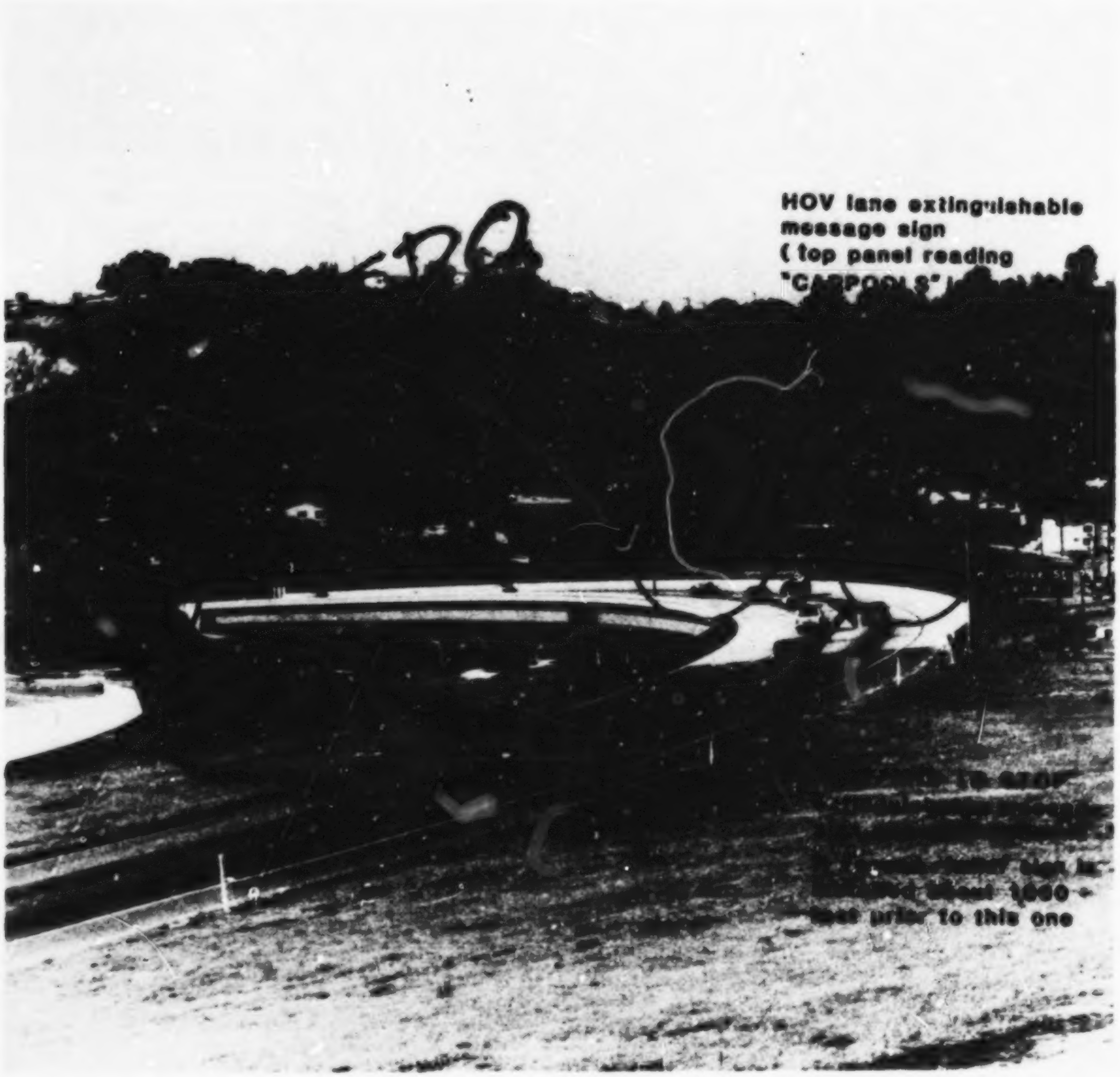

HOV lane extinguishable message sign
(top panel reading
"CARPOOLS" [illegible]
[illegible] to stop [illegible]
[illegible] sign is
[illegible] about 1000 -
feet prior to this one

Figure 4.23. Connector metering installation in San Diego (California)

Source: Reference (*48*)

alternative routes. Corridor control is thus the integration of urban street control and freeway control, done to achieve a full utilization of total capacity.

Inherent in the objective and scope of corridor control is that, to be meaningful, it must be traffic-responsive. Therefore, a key element of corridor control is surveillance, which is action-oriented monitoring of traffic conditions on the corridor links.

Strategy

The basic philosophy of corridor control embodies two aspects: (1) restriction and (2) diversion. Restriction comprises the limitation of demands on corridor links to less than link capacity. Diversion is the transfer of traffic from corridor links with excess demand to those with excess demand capacity. Restriction is accomplished by the coordination of regulatory controls such as ramp, mainline, isolated-intersection, arterial-street, and network controls. Diversion is induced by these regulatory controls and facilitated by driver information systems.

Integration of all these control elements involves application of the following specific techniques (*27*):

- Coordination of traffic signals on frontage roads and parallel alternate routes
- Coordination of traffic signals at freeway interchanges with arterial cross streets, such as at a diamond interchange (*49*)
- Coordination of the ramp-control queue-override feature with the frontage-road cross-street intersection control to prevent queuing across these intersections
- Provision of turning phases at the frontage road and other alternate route intersections with cross streets which lead to freeway ramps
- Coordination of ramp control and frontage-road operations
- Detection of incidents and provision of appropriate response to rapidly remove their impact on traffic flow

Several research efforts are in progress dealing with the development of an integrated corridor control strategy which will coordinate freeway control with other roadway and driver information elements. Perhaps the most advanced U.S. effort is the Integrated Motorist Information System (IMIS) being implemented on Long Island, New York. The extensive planning and feasibility analysis performed for this project has produced a handbook of value to others in developing a corridor control system (*50*).

Incident Management

Delays and hazards caused by random events constitute a serious freeway operations problem. Referred to as incidents, these events vary significantly in character and include such things as traffic accidents, disabled vehicles, spilled loads, adverse weather conditions, and congestion caused by special events. Because neither the location nor time of these random events is predictable, the resulting congestion cannot be remedied by use of the same solutions suitable for recurring problems.

Experience has shown that nonrecurring problems happen frequently in day-to-day freeway operation and can create considerable congestion, especially if they occur early in peak demand periods. Synthesis of research on a number of projects indicates an incident frequency of 200 incidents per million vehicle-miles (mvm) of travel (*51*). Relating this to a 6-lane freeway segment 10 mi long with shoulders and a rush-period volume split of 5,000 vph in the heavy direction and 2,600 vph in the light direction, and a 2-hr rush period each peak, 10,000 incidents per year would be expected during the peak periods. Further, these 10,000 incidents are likely to be distributed as follows:

- 400 incidents will occur in and block the mainline:
  - 120 will require only driver action to resolve the problem; and
  - 280 will require assistance. Of these, 60 will be accidents with 50 blocking only one lane and 10 blocking two or more lanes. Of the remaining 220 disablements, 210 will block only one lane while 10 will block two or more lanes.
- 9,600 incidents will make their way to the shoulder:
  - 400 will be accidents, with 170 being minor enough for the motorists to resolve themselves. The remaining 230 will requires assistance
  - 9,200 will be vehicle disablements, with 1,720 requiring assistance

Freeway incident management, as described in this Handbook, refers to a coordinated and preplanned approach used to restore freeway traffic to normal operation as quickly as possible after an incident has occurred by using human and mechanical resources. This approach is built around a systemized process which includes incident detection, response, and onsite management.

Many of the freeway incident management options involve low-cost or minimum investment actions of an administrative or organizational nature. Specific examples include the designation of offsite accident investigation sites, implementation of a policy concerning controlled use of emergency vehicles' lights, establishment of wrecker contracts, cooperation with media representatives, alternate route preplanning, and development of reference documents for use in hazardous waste emergencies.

The following sections provide discussion of the incident management elements of detection, response, and removal, all of which have the primary objective of clearing an incident as quickly as possible.

153

Detection. The 8 major surveillance concepts that have been used to detect freeway traffic incidents are as follows (*27*):

- Electronic surveillance
- Closed-circuit television
- Aerial surveillance
- Emergency call boxes
- Emergency telephones
- Cooperative motorist-aid systems
- Citizen-band (CB) radio
- Police and service patrols

Electronic Surveillance — Incident detection by electronic surveillance involves real-time computer monitoring of traffic data obtained from vehicle detectors on the roadway to determine when and where incidents have occurred (see Chapter 5, for discussion of detector locations). The development of analytical procedures (or algorithms) to be used by computers for the automatic detection of freeway incidents has been the subject of considerable research (*52-59*). As yet, no one algorithm has been generally accepted as being superior to all of the others. In evaluating the performance of incident-detection algorithms the following measures are usually used:

- Probability of detecting an incident, given that it occurred
- Probability of generating false alarms
- Time-lag between occurrence of an incident and its detection
- Probability of detecting the end of an incident

When a traffic incident occurs on a freeway, the capacity is reduced at that point. Depending on the magnitude of capacity reduction and the traffic conditions prevailing at the time (light, medium, or heavy), the traffic data collected may exhibit different patterns (*56*). The pattern that is most easily discriminated from those associated with incident-free conditions is the one that develops when reduced capacity at the incident site is less than the volume of oncoming traffic, resulting in a queue developing upstream.

In this case, four distinct regions of traffic flow occur in the vicinity of an incident. As indicated in Figure 4.24, the traffic flow in Regions 1 and 4 is initially unaffected by the incident and is normal. In Region 2, immediately downstream of the incident, the traffic flow is noncongested because the volume is equal to the capacity of the bottleneck caused by the incident, which is less than the capacity of the freeway in Region 3. Therefore, speed is higher than normal, and density is lower than normal.

The boundary between Regions 1 and 2 moves upstream, and the boundary between Regions 3 and 4 moves downstream. These boundaries, which are commonly referred to as a shock wave and an expansion wave, respectively, move at speeds which are functions of the operating flow rates before and during the incident. Thus, the extent of congestion caused by an incident depends on the normal traffic volume, the capacity of the bottleneck created, and the length of time before the incident is removed.

Therefore, most freeway incident-detection algorithms involve the determination of changes in certain traffic-flow variables (such as volume, speed, occupancy, kinetic energy, or various combinations of these), that are believed to be caused by, or correlate with, the occurrence of incidents. If detected changes in the traffic-flow variables with respect to time and/or space prove greater than the predetermined threshold values, the occurrence of an incident would be indicated.

In general, incident-detection algorithms can be categorized as pattern-recognition algorithms and time-series (smoothing) algorithms. To a large extent, pattern-recognition algorithms deal with current traffic patterns and pay no attention to past values of traffic variables (*52-53, 56, 58-59*). Conversely, time-series algorithms utilize short-term forecasting techniques to identify the sudden changes in traffic stream behavior which occur during incidents (*54-55, 60-61*).

An example of the pattern-recognition algorithms is the one developed by the California Department of Transportation, commonly called the "California algorithm" (*52*). This algorithm uses traffic occupancy to sense congestion changes that indicate an incident has occurred. One-minute occupancies updated every 20 to 30 sec are compared between adjacent detector stations. The algorithm signals the occurrence of an incident if the following test conditions are met:

1. The difference between the occupancies of adjacent detector stations is greater than, or equal to, a predetermined value, k_1.
2. The percent difference between the occupancies of adjacent detector stations with respect to that of the upstream detector station is greater than, or equal to, a predetermined value, k_2.
3. The relative percent change between the present occupancy and the occupancy of the preceding sample for the downstream detector station is greater than, or equal to, a predetermined value, k_3.

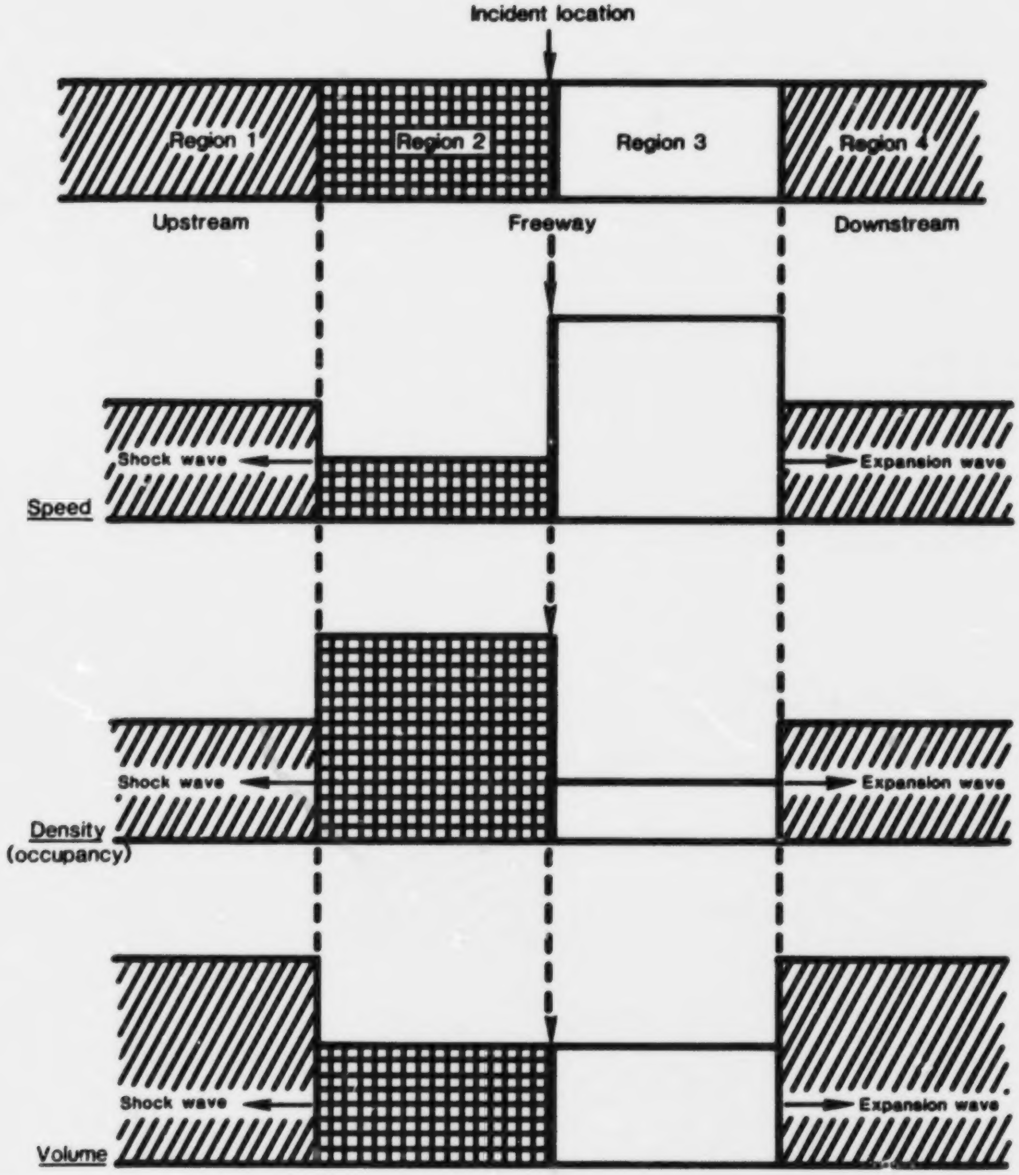

Incident location
Region 1
Region 2
Region 3
Region 4
Upstream
Freeway
Downstream
Speed
Shock wave
Expansion wave
Density
(occupancy)
Shock wave
Expansion wave
Volume
Shock wave
Expansion wave

Figure 4.24. Graphical summary of the theoretical impact of a freeway incident on traffic flow

If all of these conditions above were satisfied, the occurrence of an incident would be indicated. The predetermined values, k_1, k_2, and k_3 are established in accordance with both location and time of day to account for changing traffic patterns on the freeway. Typical values during peak hours for these constants are $k_1 = 8$, $k_2 = 55$, and $k_3 = 15$ for a normal section; however, they can be increased to $k_1 = 15$, $k_2 = 60$, and $k_2 = 25$ for areas where there is a normally restrictive bottleneck. As these values are increased, the chances of an early detec-

135

tion are reduced; however, with the reduced false alarm rate associated with these higher values, confidence in the system can be developed.

A 7-month online test of the operation of this algorithm was conducted on the 42-mi freeway loop in the Los Angeles Area Freeway Surveillance and Control Project (LAAFSCP) (*52*). Loop detectors were installed at approximately half-mile intervals. During the test period, over 2,700 congestion-producing incidents occurred on the 42-mi loop, and, of these, over 80 percent were detected in under 4 min. Over 90 percent of all congestion-producing incidents were detected, with 32 percent false alarms for all periods of the day. Other findings of this study yielded these specific conclusions:

- Congestion-producing incidents can be detected
- The majority of incidents (90 percent) affect traffic in a similar manner
- The degree of congestion (i.e., length of backup or capacity reduction) affects the speed of detection
- Detector spacing affects both number and speed of detections
- The location of detectors with respect to entrance and exit ramps affects the effectiveness of any detection algorithm
- Sensitivity of detection directly affects the false alarm rate

Electronic surveillance provides a continuous, networkwide monitoring capability at comparably low cost. In addition to serving the purposes of incident detection, electronic surveillance can be used to provide not only control parameters for traffic-responsive control but also measures of effectiveness for system evaluation. However, in regard to incident detection, electronic surveillance does have some disadvantages.

- Incident-detection algorithms have yet to be perfected that detect all congestion-producing incidents without generating a large number of false alarms. Some traffic patterns associated with incidents cannot be easily detected since they usually occur when the prevailing traffic conditions are light and the impact of the incident is not so severe, or when traffic conditions are heavy and the reduced capacity at the incident site is greater than the downstream volume. In addition, some traffic patterns occurring under incident-free conditions are similar to incident patterns, and tend to produce false alarms.
- In recognition of the need for improved incident-detection algorithms, a research project titled "Analysis and Remedies of Freeway Traffic Disturbances" was sponsored by the Federal Highway Administration. This project has led to the development of 10 new algorithms which were tested and evaluated using surveillance data obtained from the Los Angeles and Minneapolis freeway systems (*62*). These algorithms have been further evaluated by the Illinois Department of Transportation at the Chicago Freeway Surveillance and Control System to determine their technical acceptability and ease of implementation (*63,64*). A more detailed discussion of incident detection algorithms may be found in the FHWA publication, *A Freeway Management Handbook* (*65*).
- The nature of the incidents cannot be determined by electronic surveillance; therefore, some other form of followup surveillance is required to determine the necessary response.

Closed-Circuit Television — Closed-circuit television (CCTV) is primarily used in freeway control systems to confirm the presence of an incident and quickly determine its nature and severity. This initial assessment of incident severity is valuable in assuring the dispatch of an appropriate response to deal with the event and builds credibility with the response agency in that they are not sent on false alarms. Another benefit of CCTV is that it permits the use of less discriminating incident detection algorithms, since the first response to an algorithm generated alarm is to visually confirm the incident.

Freeway surveillance using CCTV has been employed in several cities, both in the United States and Japan, including Tampa, Detroit (*43*), Dallas (*66*), Houston, (*67*), Osaka (*20*), and Tokyo (*21*). A summary of CCTV surveillance applications is presented in a later section of this chapter.

Aerial Surveillance — Aerial surveillance from helicopters and small airplanes is used by many police authorities and commercial radio stations to detect incidents and provide alternate route advisory bulletins to motorists on freeways and urban streets. But, because of the wide area which is usually covered, this technique is generally not conducive to rapid detection and removal of incidents. Also, this method of incident detection is expensive, and its effectiveness is limited by weather conditions during which incident occurrence is usually higher. In certain metropolitan areas, traffic surveillance services with multiple aerial and ground observers have been organized to provide a reliable service to multiple broadcast agencies. Their effectiveness is dependent on the responsiveness of the broadcast media, but such services may provide valuable direct information for a command/control system.

A study by Weinberg and others (*68*) of the effectiveness of airborne-observer systems in rerouting traffic as a response to incidents has indicated that annual savings in motorist delay time could justify the use of a helicopter or light-airplane observer system. However, in general, it has not yet been shown conclusively that aerial surveillance is economically feasible in comparison with other surveillance techniques.

The feasibility of CCTV inside a helicopter was tested as a follow-up to electronic surveillance in the Los Angeles Area Freeway Surveillance and Control Project (*69*). Indications were that this system was not feasible, primarily because the response time of the helicopter to incidents was too slow for use in the motorist information system. Fixed CCTV was considered to be the preferred alternative.

Emergency Call Boxes and Emergency Telephones — Emergency call boxes and emergency telephones are often installed along freeways to provide the motorist with a means of summoning aid. The primary difference between these two systems is that telephones transmit normal voice messages while call boxes may be limited to transmitting pulse-coded messages requesting various services (e.g., police, wrecker, ambulance, cancel, etc.). Telephones are preferable in terms of false alarms and the certainty of providing the correct response. A typical emergency call box and an emergency telephone are shown in Figures 4.25 and 4.26.

Studies (*69-70*) of properly designed motorist-aid systems indicate that they are efficient methods of signaling a motorist's need for assistance and of providing reassurance that aid will be provided. Either system is considered to be desirable. However, their usefulness as a means of incident detection is diminished if electronic or CCTV surveillance is also used. When located on the edge of the freeway shoulder they may present a safety hazard, but if located off of the freeway (e.g., at the head of an exit ramp), they may provide less service to stranded motorists. Cost to install, maintain, and operate the system must also be carefully considered.

Recently, the Michigan Department of Transportation installed 70 motorist-aid telephones on 15 mi of I-94. During the 27 months of their operation, the Michigan State Police responded to 6,789 calls and provided service to 4,515 motorists, including 833 traffic incidents and 27 medical emergencies. Significant savings to the motorists have been reported in terms of vehicle-hours of travel, fuel consumption, air pollution, and potential accidents which were avoided (*71*).

Cooperative Motorist-Aid Systems — The assistance of motorists in reporting difficulties of other motorists who need help is utilized by cooperative motorist-aid systems. The major advantage of this concept is its low cost of installation and operation. Also, a stranded motorist does not have to leave his vehicle in order to summon aid.

Citizen-Band (CB) Radio — One means by which incidents on freeways and urban streets can be reported is by citizen-band (CB) radio. Drivers of CB-radio-equipped vehicles report observed incidents to a central control center, where an operator in 2-way communication with the incident reported transmits the necessary information via telephone to the appropriate authority, which in turn dispatches the required response and/or assistance.

A major advantage of the CB-radio-surveillance concept of incident detection is that determining the nature of the incident and the type of response required can be more readily accomplished. However, the detection capability of the system is a function of the number of reporters on the road at any given time who have an interest in reporting their observations.

In August 1980, experiments were conducted with a CB-radio surveillance system along I-96 between Grand Rapids and Detroit, Michigan. The Broad Emergency Assistance Radio system (BEAR), consists of 10 remotely controlled CB base stations spaced at 10-15 mi intervals (*72*). The system relays motorists' reports of incidents and needs for assistance on CB Channel 9 (the emergency frequency) to state police headquarters in East Lansing, as shown in Figure 4.27. The relay from remote antennas is accomplished by a combination of leased telephone lines and an existing microwave communication system. State police radio operators and local volunteer CB groups provide full-time monitoring of Channel 9 and dispatch the proper aid to the caller.

The BEAR System is the first CB-radio surveillance system in the United States which has qualified for Federal Highway Administration funding. During its first operational year, the BEAR System operators handled 4,115 calls for an average of 11.3 calls per day, while volunteer groups handled 1,920 calls that fell within the influence area served by the 10 relay towers. About 16 percent of the calls reported freeway accidents of different types, 50 percent reported need for motorist assistance (flat tires, mechanical problems, no gas, etc.), 1 percent reported medical emergencies, and the remaining calls reported other types of incidents (fire, highway hazard, abandoned vehicle, etc.).

The following conclusions and recommendations have been made by the BEAR project staff:

- The system is an effective and feasible method of providing direct communications between the state police and motorists.

- The concern of providing aid to motorists without CB radios proved to be unwarranted. A survey conducted by the Michigan Department of Transportation revealed that 49 percent of the vehicles traveling on I-96 had a CB antenna. In addition, the BEAR data indicated that 60 percent of all calls were made by motorists reporting an incident in which they were not a participant.

- The number of false calls received was very small and did not represent an operational problem (only 5 obvious false calls were reported during the evaluation period).

- Total equipment failures were minimal. However, to maintain operator confidence, it was recommended that the operation of each CB base station be checked at least once a week by means of signal checks from a mobile unit.

- It was determined that antenna height should be limited to 50 ft, with a planned 4-mi-radius of coverage.

The ability to listen in on CB radio conversations along various sections of a freeway can be extremely useful in supplementing other data sources on incidents. Chicago, for example, provided CB receivers in cabinets along the freeway with an ability to monitor them at a central location. In this way, systems operators were able to hear what the problems were along the freeway.

Police and Service Patrols — The most common form of incident detection on freeways and urban streets is by police patrols. The primary advantage of this type is that the response to an incident is immediate once it has been detected. However, the effectiveness is limited by the high cost of manpower, which usually confines the use of police patrols to the busiest roads during the peak periods. Also, the availability of police for patrols is subject to other, more urgent demands of police work, including priorities of public safety needs. In general, incident detection is not really an efficient use of police time because many incidents do not require any police response. It is probably more economical to use police patrols as a followup system in response to calls received via some other form of incident detection.

In some cases, service patrols are provided instead of, or in addition to, police patrols, especially during peak periods on heavily traveled routes. The service patrols are equipped to provide such routine assistance to stranded motorists as fuel, oil, water, tire change, and minor

Figure 4.25. Emergency call box

Figure 4.26. Emergency telephone

mechanical repairs at the roadside. As in the case of police patrols, service patrols generally provide a rapid response to motorist needs, but they are expensive.

Incident Response. The optimal strategy for a surveillance and control system during a capacity-reducing incident is to immediately restrict or prevent additional vehicles from entering the freeway upstream of the incident, with these drivers advised to enter downstream and take advantage of uncongested freeway conditions there. As indicated in Figure 4.28, the diversion of some freeway users will allow normal operating conditions to be restored sooner, and the total delay to on-freeway users will be reduced by the shaded area (*73*).

The desired demand redistribution can be facilitated by informing potential ramp users of congestion specifically caused by an incident. Variable-message signs, ramp-condition information signs, and commercial radio can be used to provide timely, credible information to motorists of incident occurrence and clearance. Clearly, communications facilities and cooperation with the media should be pursued in these regards.

Metering rates upstream can be more acceptably reduced, or the ramps closed, if the reason is an incident and drivers are made aware of the reason. Concurrently, drivers can be advised to proceed along alternate routes with the knowledge that, whatever the downstream operations are at the time, downstream capacity will be available by the time the diverted drivers reach the downstream entrance ramps. This, of course, can be accomplished only if an immediate response to the incident is made by the surveillance and control system. Once an incident has begun, downstream demand will slacken within minutes. To utilize the downstream excess capacity fully, there must be immediate diversion of upstream vehicles. This is practical only when and where adequate capacity exists on diversion routes.

Incident Removal. Incident removal normally involves preplanning for, and the actual provision of, emergency services (police, fire, and ambulance), and repair and tow services. Of course, essential to the success of any incident-removal scheme is the cooperation of the agencies responsible for providing the needed services, as well as the coordination of the appropriate responses.

Rapid removal is critical to minimizing delays following an incident. Techniques such as providing off-freeway accident investigation sites (as is done in Houston, Texas), and policies restricting the use of flashing lights on emergency vehicles can be very beneficial in effective incident response. Preplanning for response should be directed toward alternative routes, interagency cooperation, identification of response resources, and anticipating special needs, such as handling hazardous waste spills.

Three examples of effective incident response organizations are:

- Chicago Area Emergency Traffic Patrol — On Chicago area expressways, a special, radio-equipped fleet of trucks is used in the management of incidents (*74*). This public minute man patrol service which has been in operation since 1961, has served as an international model for coping with expressway incidents. The primary objective of the patrol is to keep the moving lanes clear of accident vehicles, disablements,

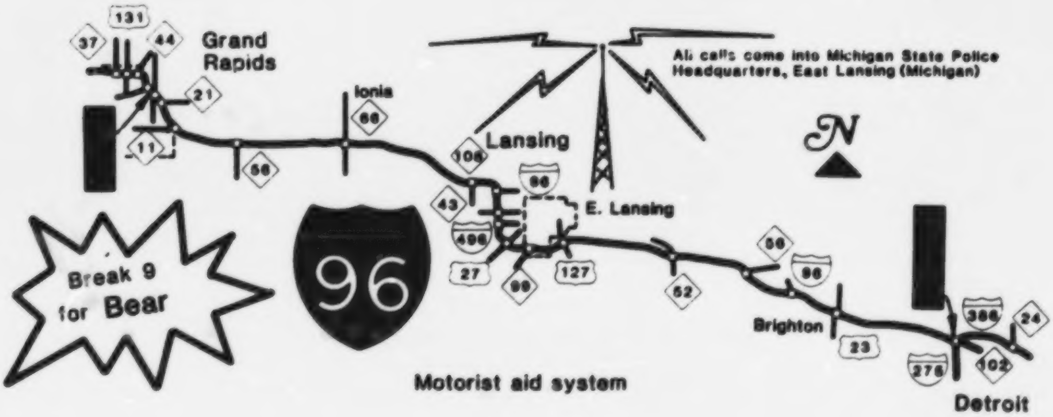


Figure 4.27. The BEAR System, Michigan

Source: Reference (*72*)

and debris. Its operation covers over 135 mi of the Chicago-area expressway system on a 24-hr/day, 7-day/wk basis.

The patrol vehicles are equipped and the drivers trained to handle almost any type of incident likely to occur on Chicago area expressways, including accidents, disabled vehicles, and small fires. The service is termed "emergency" in that assistance is directed towards actual emergencies and hazardous situations. Enough help is provided to remove or reduce the exposure to high-volume, high-speed traffic. For example, towing is only provided for relocating vehicles to shoulders or frontage roads from where the motorist arranges for private towing. Disabled vehicles are not repaired by patrol drivers; but gasoline, water, air for tires, and the loan of some small tools are provided.

All patrol services are free of charge, except for gasoline. Upon receipt of two gallons of gas, a motorist is presented with an invoice requiring payment to be mailed to the State of Illinois. More than 75 percent of these charges have been voluntarily paid.

The Illinois Department of Transportation (IDOT) Communications Center serves as the coordination unit for the patrol, handling all incoming reports of incidents and, through a separate patrol radio frequency, directing the nearest available patrol unit to the scene. The communications center maintains radio or direct telephone links with the Chicago Police, State Police, Chicago Fire Department, Chicago Traffic Engineering Center, Illinois Tollway Commission, other IDOT vehicles on two additional radio frequencies, and local radio stations operating private traffic report helicopters. Over 20,000 radio messages per month are logged by the patrol.

An electronic surveillance network also is used to detect incidents which may or may not have been reported by the patrol or other sources. Early detection of incidents by electronic surveillance or CB monitoring enables the patrol to be radio-directed to the site of an incident to expedite its removal. In some cases, such incident detection has resulted in response action beginning at the scene some 15 to 20 min before the problem was reported through another source. On the other hand, the patrol has assisted at thousands of incidents which do not noticeably disrupt traffic flows, possibly due to the patrol action preventing minor, but hazardous situations from developing into more serious problems.

- Los Angeles Area Freeway Surveillance and Control Project (LAAFSCP) — One of the most sophisticated incident-removal systems in operation is that of the Los Angeles Area Freeway Surveillance and Control Project (LAAFSCP) (*68, 69*). This system features a multidisciplinary, incident-management team, which represents the disciplines of highway patrol (i.e., police), maintenance, and traffic engineering. The team operates from the control center where it has access to incident-detection information and the communication facilities necessary for dispatching required incident removal responses, such as the following:

  - ☐ Police, fire trucks, and ambulance for accidents
  - ☐ Maintenance equipment for spilled loads or damaged highway facilities
  - ☐ Tow trucks for removing damaged or stalled vehicles
  - ☐ Presentation of traffic advisories to motorists via variable-message signs and commercial radio
  - ☐ Change in metering rates at entrance ramps upstream of the incident

It has been concluded that the LAAFSCP system of incident management has effectively cut incident-

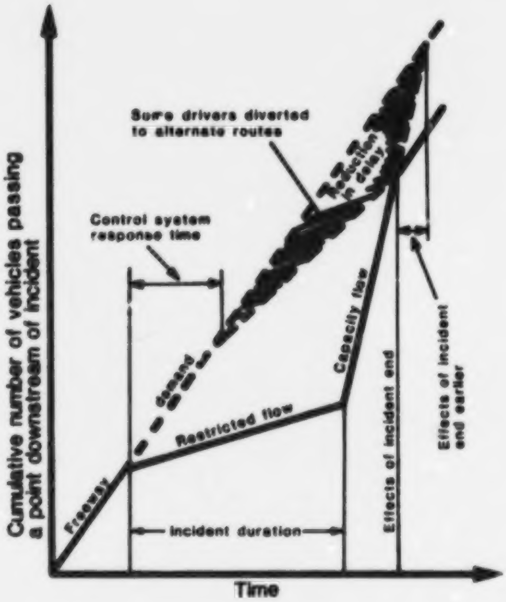


Figure 4.28. Surveillance control response to a capacity-reducing incident

Source: Reference (*15*)

caused vehicle delay in half, which represents a reduction in delay to motorists of nearly 35,000 veh-hr/month (*28*).

Experience with the LAAFSCP system of incident management has indicated the following principles of onsite incident management (*75*)

- ◻ Only vehicles and persons required for assistance should be at the scene
- ◻ Where possible, response vehicles should be parked out of sight
- ◻ Consideration should be given to removing damaged or stalled vehicles after peak periods, particularly when the vehicles are not blocking a travel lane or area out of sight
- ◻ Flashing lights should be used sparingly
- ◻ Vehicles and other evidence of the incident should be removed immediately
- ◻ Minor traffic citations should not be issued during peak periods
- ◻ Accident investigations should be completed off the roadway

Most of the above principles are concerned with minimizing the amount of activity on the roadway at the scene of an incident in order to reduce the amount of congestion caused by gawking.

- Tampa Low-Cost Freeway Incident-Management Demonstration Project — Some low-cost options for freeway incident management were field-tested and evaluated on the I-275 Howard Frankland Bridge in Tampa, Florida (*76-77*). The project involved cooperative efforts between the Florida DOT and local agencies in the Tampa - St. Petersburg area. The developed options have been classified into the following four categories:
  - ◻ Surveillance options — The objective of surveillance options is to enhance the capabilities of low-cost incident-detection techniques such as increasing the frequency of police patrols and monitoring CB radio to obtain incident information.
  - ◻ Administrative options — The administrative options are intra-agency activities intended to improve the ability of an agency to fulfill its present incident management role or to expand that role to include new responsibilities. Examples of such options are the use of off-the-freeway accident-investigation sites, and an emergency-light policy that reduces the indiscriminate use of flashing lights.
  - ◻ Organizational options — The organizational options may involve several agencies and are aimed at facilitating the cooperative effort needed for successful incident management. Examples of such options are the development of contracts, ordinances, or agreements to control towing services, and the use of freeway-incident management response teams.
  - ◻ Preplanning Options — The purpose of preplanning options is to prepare and train the personnel of the agencies in charge of incident-management activities.

The results of the Tampa demonstration project have indicated the effectiveness of low-cost incident management techniques in reducing the delay caused by freeway incidents (*77*).

Television Surveillance

Closed-circuit television (CCTV) is an important element of modern traffic surveillance and control systems, particularly in building credibility with police and others who must respond to incident alarms. Early installations such as on the Lodge Freeway in Detroit (*43, 78-79*) found that CCTV systems could be very effective, but monitoring the TV screen was a tedious task. Operators tended to lose interest and failed to notice incidents immediately.

Experience has demonstrated that some automatic electronic detection means of incident *detection*, coupled with CCTV use for *verification*, is the most effective approach. Operators are not required to watch the monitors for all cameras. In operation, an incident-detection algorithm, as described earlier, processes input data from closely spaced mainlane detectors to identify the likely occurrence of an incident. The system operator can then selectively use the CCTV system to visually observe the incident location in order to verify its presence, assess response needs, and monitor activities during its clearance.

In addition to confirmation of incidents, CCTV systems have been used for remote traffic operations data collection, and to observe events such as maintenance operations. Recent research associated with the development of a Wide Area Detection System (WADS) and an imaging process for detection and data collection may lead to another potential use of CCTV systems (*80*). The State of Maryland is examining the use of compressed video transmission over voice-grade telephone lines.

The basic elements of a closed-circuit television system, as shown in Figure 4.29, are:

- Cameras

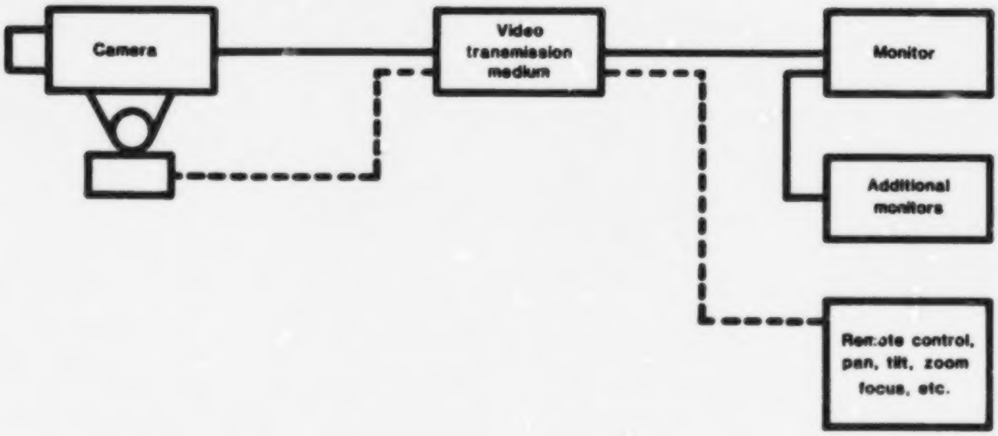

Camera
Video transmission medium
Monitor
Additional monitors
Remote control, pan, tilt, zoom focus, etc.

Figure 4.29. Basic elements of a CCTV system

- Monitors
- Peripheral devices
- Transmission system

Cameras. In planning CCTV systems, the designer must consider the following factors in selecting the proper type of camera:

- Type of pickup tube
- Type and rate of scanning
- Number of lines of horizontal resolution
- Video bandwidth
- Ambient operating conditions
- Camera encasement and accessories (zoom, pan, tilt)
- Sensitivity during night operation
- Automatic target control capability

A detailed discussion of these factors is provided by Richard and Bushnell (*81*) and McCasland (*82*). In addition further information is included in the FHWA publication *A Freeway Management Handbook* (*65*).

Monitors. In the control center, primary consideration must be given to a suitable arrangement of monitors to permit effective utilization of the information presented. The specifications for performance of the monitors would, of course, be dependent upon compatibility with the total system. The function of the monitor is to provide observation of system operation. Although choice can be made as to the size of the monitor, most systems include a larger monitor to provide a picture from which detail can be adequately obtained and that can allow fine control of camera functions. Black-and-white monitors between 8 and 21 in. are generally specified, with the master monitors ranging between 14 and 21 in.

Peripheral Devices. The only basic devices considered to be peripheral to television systems are video tape recorders. As with the monitors, however, they must be compatible with the rest of the system. They offer a recording medium from which transient phenomena may be subjected to analysis. A provision should be made to interface through the master monitor in such a manner that recordings can be taken through any camera in the system. The attachment of a recorder to each monitor is not generally considered to be either necessary or economical.

Transmission Systems. The two basic methods of providing CCTV transmission are direct video and radio-frequency (RF) distribution. Several media may be used for the distribution of the television signals between camera and monitor. Direct video transmission between cameras and monitor may be attained through the use of coaxial cable, balanced-line video cable, microwave, and telephone type twisted-pairs (for slow-scan television). Radio-frequency distribution utilizes a single coaxial cable to transmit multiple pictures.

4.6 AVAILABLE COMPUTER SOFTWARE

Computer simulation models offer the means to test alternative control strategies and geometric configurations in a controlled environment. Detailed information gathered through simulation would be virtually impossible to obtain by field tests. In many cases where many alternatives are being tested in large-scale projects, simulation is the only feasible method of estimating the impacts of different alternatives.

Simulation models are used in two ways — offline to test various alternatives, and online as an integral part of control software. These online applications typically operate under severe time constraints in that they must be executed quickly, perhaps with limited input data, in order to make some control decision for immediate implementation. In the offline mode, the availability of larger and faster computers has permitted the use of more refined and complex models.

Numerous freeway simulation models have been developed and described in the literature. Most were created for a specific purpose or type of operation. The following material, adapted from the publication *A Freeway Management Handbook* (*65*) describes the history of model development and the current 5 families of freeway corridor simulation models available. The 5 families are CORQ, FREQ, INTRAS, MACK, and SCOT. In addition, a brief reference to two online models, DIVERT and STAR, is presented.

Model History

In 1974, Hsu and Munjal (*83*) reviewed 15 freeway simulation models associated with various aspects of freeway vehicular traffic, and the models were compared against a baseline of eight desirable model features. The reader may wish to refer to the paper by Hsu and Munjal for information on these earlier models:

- Arizona Transportation and Traffic Institute Traffic Simulation Model (*84*)
- Midwest Research Institute Freeway Simulation Model (*85-86*)
- Midwest Research Institute Mountainous Terrain Model (*87*)
- Northwestern University Lane-Changing Model (*88*)
- Sinha Freeway Simulation Model (*89-90*)
- Connecticut Department of Transportation Expressway Simulation Model (*91*)
- Texas Transportation Institute Freeway Merging Model (*92*)
- System Development Corporation Diamond Interchange Model (*93*)
- System Development Corporation Freeway Simulation Model (*94*)
- Mikhalkin Freeway Simulation Model (*95*)
- Georgia Model (*96*)
- SCOT Corridor Model (*97*)
- Priority Lane Model (*98-99*)
- Aggregate Variable Models (*100*)
- Aerospace Corporation Freeway Simulation Model (*101*)

Many of these models were early versions or parts of current models. For example, Lieberman and Bullen used the Northwestern Model in the development of the INTRAS model while the SCOT Corridor Model was the early version in the SCOT family. The Priority Lane Model was an early priority-lane version in the FREQ model family, and the Aggregate Variable Models was the early version in the MACK model family (*102*)

CORQ-CORCON Model

The CORQ model developed by Yagar during 1968 to 1975 and the related CORCON model developed by Allen and Associates during 1974 to 1978 are the two in this family. In addition to their development, these models have been applied in Ottawa, Toronto, and San Francisco by the developers (*102*)

CORQ, written in FORTRAN IV, gives detailed treatment of the critical elements of a corridor in terms of traffic flow, capacity, queuing, and delays. It is related to another model, FREQ, which emphasizes the modeling of freeway queues (*103*). CORQ is a form of microassignment technique, but it is different from the Brown and Scott technique (*104*), although both can be used for microanalysis of areas that are about 500 blocks large. The methods accomplish this by totally different micromodeling procedures. The Brown and Scott model considers all intersections, but CORQ handles only major intersections, the freeway interchanges, and freeway and surface-street links between them. However, it gives a more detailed treatment especially to the intersections. It also can be used for much larger areas if, for example, only the freeway network needs to be modeled. Another major difference is that CORQ treats all time-varying demands, and the Brown and Scott model treats only homogeneous demand tables with a constant origin-destination (O/D) pattern, although it does allow the rate of demand to vary with time (*105*).

The basic method of CORQ is to divide the peak period into a set of sufficiently short time slices of common length so that the rates of demand between the various O/D pairs can be considered constant for about 15 min. This allows the time-varying demand to be expressed as

143

a set of O/D matrices representing the respective time slices; each slice has stationary demands. The O/D matrices are assigned to the network sequentially in time. This allows temporary oversaturation of network links. That is, in any time slice, certain network links may have more demand assigned to them than they can serve. Excess vehicles queue on upstream links and are reassigned to their destinations in the succeeding time slices from the points at which they queued. The assignment is based on the principle of minimum individual travel cost, and the minimum cost path may include some time in queue (*105*).

CORQ has the capability of changing network characteristics at the beginning of each time slice because capacity variations may be as important as demand variations (for example, those that simulate transient traffic controls such as time-varying, ramp-metering rates).

The following outlines the logic of the model:

- Routine for each time slice:
  - Note any changes in network characteristics that take place in a time slice.
  - Set O/D matrix equal to demand for the new time slice plus any queues from previous time slice.
- Routine for each incremental assignment:
  - For each origin node, O_i, having some demand, find the tree of shortest paths to all destinations.
  - For each destination node, D_j, work back to the origin, and note the first point of congestion in the O/D path.
  - For each destination node, D_j, tentatively assign those flows and queues that would result if all the remaining demand from O_i to D_j were assigned.
  - Find the critical sublink that limits the fraction of the tentatively assigned flows and queues that actually can be assigned in that increment.
  - Assign the appropriate fraction of the tentative assignment as determined by the critical limiting link.
  - Estimate the weave section capacities on the basis of assigned flows.
  - If it is desired to dynamically share the merge capacity, estimate the component capacities for each merge on the basis of weave capacity, respective merge entitlements, and assigned merge flows.
  - Update the statistics for each link.
  - If the entire O/D matrix has not been assigned, perform the incremental assignment routine again (*105*).

The CORQ model was tested on the Ottawa Queensway corridor (*106*). The flows and queues that it initially predicted were reasonably close to those measured in the field. Therefore, it was calibrated to actual flows and queues, and applied in testing alternative traffic-control schemes (*107*). It was further validated in application, where it demonstrated its sensitivity in modeling the effects of various strategies and its power in suggesting alternative paths around bottlenecks.

The data requirements for CORQ are of the type generally collected when doing a freeway control study. These include capacities, counts, queue sizes, travel times as a function of flow, and O/D information on users who could or should be affected by controls. Unless these data are already available, the task of collecting the data solely for use in the model may be prohibitive.

The CORCON model developed by Allen and Easa (*108-112*) is an analytical procedure for predicting traffic volumes, queuing conditions, and travel times in a freeway corridor. Traffic demand can vary over time and is assigned to a freeway and surrounding arterial street network. The minimum path algorithm can incorporate turn prohibitions. A major characteristic of the CORCON Model is its link-node representation that simplifies network representation by allowing more than one directional roadway link to have common upstream and downstream nodes and automatically avoid illogical paths in the network (*102*).

The data requirements for CORCON are similar to those of CORQ. Origin/destination demands, link volumes and queues, flow versus travel time relationships, capacity information, and network turn prohibitions were collected for using CORCON on a study in Toronto by Allen et al. (*112*). In the Toronto study, CORCON was used for the predicting traffic-operating characteristics in the corridor network before and after entry control. The model can be used not only to evaluate the effects of freeway ramp metering but also to evaluate the impact of a wide range of TSM strategies (*112*).

Because of dimensioning constraints in the currently available computer program, it may be difficult to apply CORCON to very large corridors (5 by 25 mi). This can be accommodated by either increasing the dimension sizes, analyzing two or three smaller subsections of the corridors separately, reducing the amount of coded network detail, or some combination of the preceding.

FREQ Model Family

Work on the first model of the FREQ family of models began in 1968 at the University of California at Berkeley. From this first model, FREQ (*113*), extensions and refinements were made to produce FREQ2 and FREQ3, with particular attention being directed to shock wave analysis, computer efficiency, and output format (*114-115*).

In the early 1970s, FREQ3CP, FREQ3D, and FREQ3C were developed and incorporated priority-entry control, design improvement, and normal-entry control optimization submodels, respectively (*116-118*).

The latest versions in use at this time are the FREQ7PE and FREQ7PL models (*119-121*). The FREQ7PE model, a macroscopic decision model of a freeway corridor, is used primarily for the evaluation of priority-entry and normal-entry control on a directional freeway. The model can also be used for evaluating design improvements with or without freeway-entry control. The model predicts a timestream of impacts and traveler responses. The impact assessment includes travel time, fuel emissions, and noise while demand forecasting includes spatial and modal traveler responses in increments during the first year of operation.

The FREQ7PL model is a macroscopic model of a freeway corridor, used primarily for the evaluation of reserving lane(s) on freeways for carpools and/or buses. The model can also be used for evaluating design improvements with or without priority operation. The user selects the priority lane(s), design configuration, priority cutoff level, and time duration of priority operations. The model automatically modifies the demand and supply sides of the model, and predicts a time stream of impacts and traveler responses. The impact assessment includes travel time, fuel, emissions, and facility costs while the demand forecasting includes spatial and modal traveler responses in increments during the first year of operation. FREQ8PL and FREQ8PE, the latest in the FREQ family, are also beginning to be used.

The FREQ family of models is written in FORTRAN IV and can be operated on IBM and CDC computer systems. As with the other models, the data requirements to operate the FREQ models are quite extensive. The freeway is broken into homogeneous subsections that are usually stretches of freeway between on-ramps and off-ramps, changes in freeway width, etc. The physical characteristics of the freeway necessary for input are as follows:

- Subsection length
- Number of lanes in subsection
- Lane width in subsection
- Subsection capacity
- Subsection truck factor
- Subsection grading
- Length of grade for subsection
- Subsection design speed

In addition to the physical characteristics of freeway subsections, the model considers ramp characteristics:

- Location of on-ramps and off-ramps
- Characteristics of special ramps (multilane ramps, left-hand side ramps, etc.)
- Ramp metering limit and/or capacities

The FREQ models also require demand data, which consists of the following:

- An origin/destination table for each time slice — This may be in the form of traffic counts or hourly rates and may be either measured or simulated.
- Passenger volume data — In some cases, it is desirable to measure passenger throughput (as in priority entry control simulation). The user may vary the average vehicular occupancy during each time slice.

For the FREQ7PE model, data are also required on the arterial capacity and flow rates, as well as a measure of the progression along with the arterial. FREQ models are supported by the University of California, Berkeley.

INTRAS

INTRAS was developed for use in studying freeway incident detection and control strategies (*122*). It is based on knowledge of freeway operations and surveillance systems, and it incorporates detailed traffic simulation logic developed and validated for use in the model. The INTRAS model is a microscopic model which uses car-following and lane-changing algorithms to simulate the movement of individual vehicles. For this reason, it has the capability of examining both traffic control and geometric alternatives, even in complex freeway design situations such as interchanges.

To allow simulation of freeway control policies, including ramp metering and diversion, the capability of modeling the off-freeway environment is included in INTRAS. This surface traffic modeling is patterned after the logic of the UTCS-1 simulation model (*123*).

To facilitate the simulation of closed-loop incident detection and control, as well as offline traffic analysis, the

INTRAS model contains a realistic surveillance system simulation capability. The ability to visualize vehicle trajectories, and contours of measures of effectiveness (MOE's) in the time-space plane, is included in INTRAS via a digital plotting module. INTRAS also contains a statistical analysis module that permits comparison of MOE's from different simulation runs or field data, utilizing standard parametric and nonparametric tests.

Finally, a fuel-consumption and vehicle-emission evaluation model is built into INTRAS, patterned after a similar module developed for the UTCS-1 (NETSIM) simulation model.

INTRAS allows the user to simulate an incident at any location on a freeway link and for any length of time. The incident may block one or more lanes or be confined to the shoulder.

Three types of traffic detectors can be simulated by INTRAS: Doppler radar detectors, short inductance loops, and coupled short inductance loops.

At each freeway on-ramp, the user may simulate one of the following 4 types of ramp control: clocktime metering, demand/capacity metering, speed-control metering, and gap-acceptance merge control.

The data required for input to INTRAS include geometric data to describe the links, such as link length, number of lanes, lane channelization, type of link, grade, radius of curvature (for freeway links) percent of superelevation, and pavement type. Operational data required for input include entry-link flow rates, percentages of intercity buses, heavy single-unit trucks, trailer trucks, high-performance passenger cars, low-performance passenger cars, turning percentages at intersections, discharge headways, lost time, and free-flow speeds. Also required for input to INTRAS are control data to identify the type of control at intersections; i.e., stop sign, pretimed or actuated signal, the actual signal timing, ramp-control operation, location and type of detectors present, and location, type, and time of incident.

The INTRAS model is written in standard ANSI FORTRAN. The model was developed for and implemented on the CDC 6600/7600 computer series and the IBM 360/370 computer series. Since ANSI FORTRAN is used, the model may be implemented on virtually any large-scale computer having an ANSI FORTRAN compiler. INTRAS and FREFLO (described below) are supported by FHWA.

MACK Family

The MACK model and its later versions are deterministic, macroscopic models that consist basically of a set of conservation equations and a corresponding set of dynamic speed-density equations. Payne and Associates began work in the late 1960s, and models in this family include MACK I, MACK II, MACK III, and FREFLO.

In the MACK I model, the dynamics of traffic are described by the numerical solution of fluid-flow differential equations, appropriately modified to represent the traffic environment. This model generates results that exhibit all the global dynamic responses to freeway traffic flow, with a minimum of computational costs. It is capable of simulating the response of the system to incidents that block one or more lanes on a section of roadway. The model does not distinguish flow by lanes.

In the MACK II model, a new equilibrium speed-density relationship and a structural change in the dynamic speed relationship involving the parameters were introduced. The MACK II and INTRAS models were applied to a segment of the Shirley Highway outside of Washington, D.C., with incident-free and incident scenarios. The authors recommended that MACK II be adopted for the purpose of making preliminary evaluations of control strategies for responding to incidents based on the qualitative agreement between MACK II and INTRAS results, and the large difference in cost between execution of the macroscopic MACK model and the microscopic INTRAS model (*124-125*).

The FREFLO model developed by Payne and ESSCOR was a successor to the MACK II model. The FREFLO model was designed to provide a basic model, perform input data diagnostics, represent incidents, model on-ramps, represent different time-of-day control periods, represent surveillance, represent 2 traffic-responsive metering schemes, provide standard measures of travel and travel time, include fuel consumption, and include pollution emissions.

The geometric data required by FREFLO consist of the number of lanes in each section, section lengths, on-ramp and off-ramp locations, and nominal section capacities. The traffic data required are densities and speeds of each section for the initial state, upstream freeway volume for each time period, and on-ramp and off-ramp volumes for each time period.

SCOT Model

The SCOT model is a combination of two simulation models: DAFT and NETSIM (UTCS-1) (*126*). It has the capability of simulating traffic patterns within an integrated freeway corridor. It is macroscopic on the freeway elements, microscopic on the ramps, service roads, major arterials, and city streets. Traffic performance measures may be computed for a wide variety of control strategies; e.g., traffic signal schedules, ramp metering policies, and bus priority schemes. The effect of these strategies on traffic flow in each element of the corridor can be determined quantitatively; e.g., the increase in freeway average speed, the growth of queues on the ramps, the number of vehicles moving through an intersection, and the location, extent, and duration of congestion.

The DAFT model is a macroscopic simulation of traffic along a network of freeways, ramps, and arterials. Vehicles are grouped into platoons and lose their individual characteristics. The platoons are moved along the freeway according to a single, prespecified speed-density relation that applies to all freeway links. Along the nonfreeway links, they travel at the specified free-flow speed for each link and are delayed at the downstream end for a time related to the ratio green time to signal cycle time (G/C) of the facing signal there and to the volume of traffic on that link. For each entry link at the periphery of the network considered, traffic volumes are specified according to destination node; i.e., the input data consist of O/D demands that vary with time. The model distributes the resulting platoons of vehicles over the network so as to satisfy these specified O/D patterns and to follow minimum-cost paths. These minimum-cost paths are calculated frequently by the model, based on current conditions. Whenever a platoon reaches a network node, its turning movement there is dictated by its minimum-cost path as it exists at that instant of time. Hence, the model produces a dynamic assignment of traffic as a by-product of the simulation.

The basic approach adopted in the design of the SCOT model was to combine the DAFT and NETSIM models appropriately. The microscopic logic of NETSIM is applied to those components of the network characterized by signalized, at-grade intersections. Here, the traffic mechanisms are so complex, because of the many conflicts common to the stop-and-go patterns of urban traffic, that each vehicle must be treated individually, and a very small time step must be applied to obtain an acceptable level of accuracy in the replication of global traffic flow. Traffic along the freeway, however, has been modeled successfully by the use of fluid-flow analogies and has often been referred to as stream flow. It was believed that applying a microscopic approach to freeway traffic would yield little in the way of additional global accuracy. Furthermore, a microscopic treatment of freeway traffic would greatly magnify computing costs and storage requirements.

The SCOT output is a dynamic history of the state of traffic on each street and intersection during the simulation period. In addition, averages for the entire network are computed. Thus, a local and a systemwide view is obtained.

The locations and durations of spillback (the extension of a queue into the upstream intersection blocking cross traffic) and the instances of cycle failure (the inadequacy of a green interval duration to discharge the entire queue) are recorded. The number of vehicles currently on each street is given. Cumulative statistical data for each street as well as the network as a whole are also available as often as desired. these include the number of vehicles that have traversed each street, the number of stops made on each street, average speed, average delay per vehicle and mean occupancy on each street and for the network as a whole, vehicle-miles, vehicle-minutes, delay per vehicle-mile, and traveltime per vehicle mile. Bus statistics are compiled separately and include the number of stops made on each street. Bus route data, such as average speed, total bus station dwell time, and total delay time for each bus route, are given.

The information required by SCOT to model a network is generally available to traffic engineers. These data fall into four sets: geometric, traffic demand, control system, and bus schedules.

Typical geometric data needed include the configuration of each street or freeway section, grades, and details of ramps and turning lanes. The number and widths of travel and parking lanes must be known as well as the locations of internal traffic generators, such as shopping centers and parking lots.

Data that describe the volume and character of traffic must be obtained. Speed-density data are needed for each freeway section. Inflow rates at the periphery of the network as well as traffic mix, i.e., ratio of number of passenger cars to trucks, the usual turning movements and pedestrian activity at each intersection, and the street free-flow speeds and rate of queue discharge, are required.

All parameters of the control strategy are needed. These parameters include the following: traffic signal timings and synchronizations; parking restrictions and lane use (e.g., right turn only); ramp-metering and bus-priority policies; and traffic-actuated logic.

Bus service data needed include bus routes, station locations and capacity, frequency of bus service, and mean station dwell times.

Online Models

Online modeling efforts for real-time control purposes started in the late 1960s and continue today. Most of the work done on this type of model was undertaken by researchers at KLD Associates, Inc., and at Sperry Systems Management, Inc. The following models were selected as examples for further discussion:

- DIVERT Model
- STAR Model

DIVERT Model. The DIVERT model is an optimization algorithm that can be integrated into the computer software of a real-time freeway corridor control system. It was developed by researchers at Sperry Systems Management, Inc., as a result of a FHWA-sponsored project concerned with the development of traffic logic for freeway corridor control. The offline version of DIVERT is called DIVSIM, and both versions are described in a report summarizing traffic diversion software applications (*127*).

The DIVERT model consists of 3 levels of control: (1) the corridor executive, which supervises the overall control process by allocating and scheduling computer resources to the various traffic control functions; (2) the corridor-level control, which optimizes traffic flow in the large by allocating traffic among the various corridor facilities such as freeways and signalized arterials; and (3) the local-level controls, which operate to optimize the use of individual facilities independently of one another, but governed by the predicted demand as determined hierarchically at the corridor level.

Based on this 3-level hierarchical control configuration, the DIVERT model is structured into 9 distinct modules, or functions, as follows:

- Corridor executive control
- Corridor-level control
    - ☐ Demand estimation
    - ☐ Corridor control
    - ☐ Corridor control message selection
    - ☐ Performance evaluation
- Local-level control
    - ☐ Ramp metering control
    - ☐ Arterial signalization
    - ☐ Incident detection
    - ☐ State and parameter estimation

Information on using the DIVERT-DIVSIM models is described by Reiss (*127*).

STAR Model. The STAR model consists of two major components, a hydrodynamic traffic-flow model and a traffic-diversion model. It was developed by researchers at Sperry Systems Management, Inc., as a result of an FHWA-sponsored project entitled "Diversion of Intercity Traffic at a Single Point with Application to the Harbor Tunnel Thruway and I-695 Bypass Route in Baltimore." The STAR model has been incorporated into the design of a practical real-time alternate routing system applicable to the Baltimore site (128-130).

4.7 HIGH-OCCUPANCY VEHICLE PRIORITY CONTROL

The concept of priority control for high-occupancy vehicles (HOV) is to provide preferential treatment for buses, vanpools, and carpools in the form of travel time advantage and reliability over lower occupancy vehicles. The preferential treatment is designed to relieve traffic congestion on freeways by encouraging better utilization of vehicular resources. The objective is to serve the people demand for a freeway corridor and reduce the vehicle demand by inducing more people to use high-occupancy vehicles. People in the HOV's directly benefit by the travel time and reliability improvement. However, people in the regular lanes also benefit because of the diversion of many trips to higher occupancy vehicles and, overall, the more efficient use of the facility. In addition to reducing congestion, higher vehicle occupancies contribute to reductions in air-pollutant emissions and total fuel consumption.

Different methods of priority control that have been used on freeways are separated facilities, reserved lanes (concurrent flow and contraflow), and priority access control (*131*). Each of these is described in the following material.

Separated Facilities

Separate roadways providing for positive separation of HOV traffic from the rest of the traffic are among the most expensive of HOV treatments since major construction is required. In some cases, though, major freeways have been constructed with space reserved in the median for such separate roadways or other transit facilities. Separate HOV facilities experience few of the enforcement and safety problems encountered by the nonseparated treatments. Separation techniques range from buffer lanes without physical barriers to parallel physical barriers. Examples shown in Figure 4.30 and 4.31 include portions of the San Bernadino Freeway (I-

148

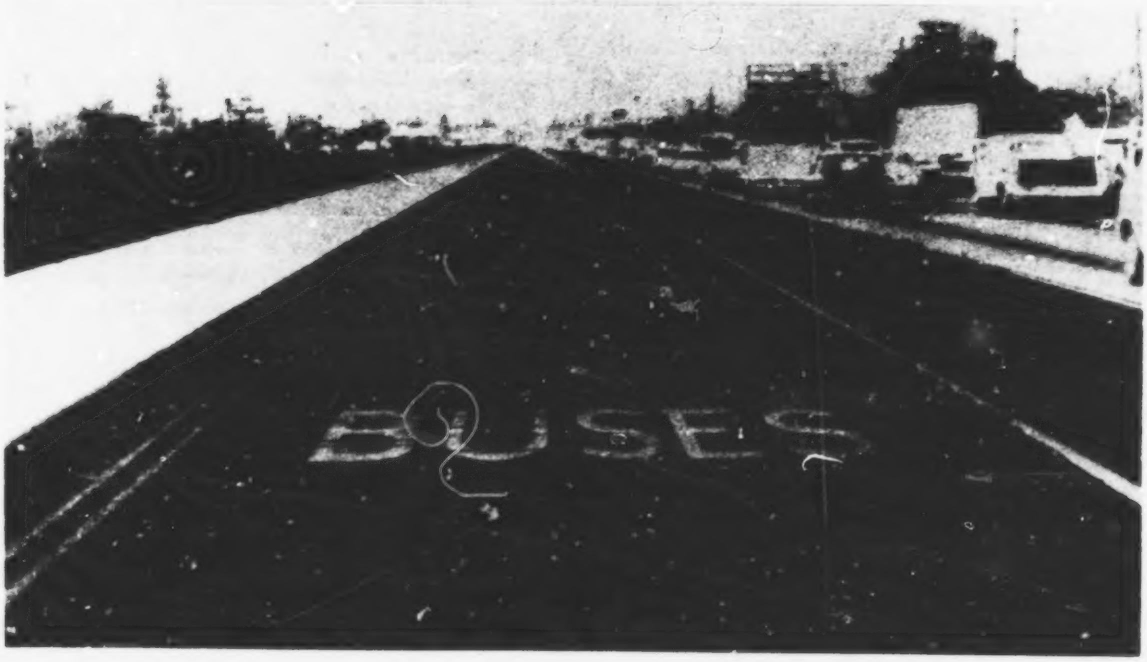


Figure 4.30. San Bernadino (California) busway

Source: Reference (*139*)

10) in California, and the Shirley Highway (I-395) in the Washington, D.C., area. These projects have been highly successful and well documented. One other project, I-66 in northern Virginia, represents an effort to provide total freeway priority by reserving all peak direction lanes for HOV use. Table 4.7 summarizes the general characteristics of selected projects in this category. Use of CCTV and variable message signs may be needed with such operations in order to monitor and control terminal and intermediate access points. Controlled use by authorized

149

BEST COPY AVAILABLE

vehicles (buses, carpools, and vanpools) is being implemented in Houston on a single lane reversible facility along I-10.

Reserved Freeway Lanes

Freeway lanes reserved for HOV use have been implemented in 2 basic configurations, of concurrent flow and contraflow lanes. Reserved lanes in the same direction as peak flow and on the same side of the median are *concurrent-flow* HOV lanes, while reserved lanes on the opposite side of the median where HOV traffic moves against the flow of traffic are *contraflow* lanes.

Contraflow lanes have received limited application, with their use restricted to specific areas of extreme congestion where the imbalance in directional flows permit consideration. In general, they have been considered to be interim actions during the definition and development of long-range solutions.

Projects in this category are shown in Table 4.8. The two projects in New York are on severely congested approaches to tunnels. In Boston, the contraflow lane for afternoon flow was abandoned after the first year of operation, and use of the morning inbound lane was discontinued in 1977 with initiation of a concurrent-flow, take-a-lane project. A more recent project, Houston's I-45 Contraflow Transit Project (*132*), has met with enormous success. Its 9.6-mi length bypassed about 6 mi of severe congestion, with time savings of over 30 min each day. From the first through the 82nd week of operation, usage increased to 10,900 vehicle trips (*133*). Its use is now (1984) over 16,000 vehicle trips per day. The use of the lane was restricted to buses and vanpools, and, for safety reasons, a rather rigid preauthorization procedure was adopted — hence, the designation authorized vehicle lane (AVL) rather than HOV. The vehicle decals used for the enforcement in this project are shown in Figure 4.32.

The concept of concurrent-flow reserved lanes designates a normal lane in the peak direction for HOV use. This preferential lane may be provided by adding a lane

Table 4.7. Characteristics of exclusive HOV roadways on grade-separated facilities

Facility	Year Opened	Length	Lane Configuration	Priority Rule	Hours of Operation	Comments
Washington (D.C.). Shirley Highway (I-395) express lanes	1969-partial	11 mi	2 reversible express lanes in median	4 or more per vehicle	11 p.m. 11 a.m. inbound	Radial corridor to CBD
	1975-final		3 and 4 unrestricted lanes in each direction		1 p.m. 8 p.m. outbound	Access ramps at 4 locations along route Major expansion of express bus service
Los Angeles (California) San Bernadino Freeway (I-10) express lanes	1973-partial 1974-complete	11 mi	2 lanes, 1 on left side of 4-lane unrestricted roadway in each direction, separated by buffer lane	Buses only, changed to 3 or more in October 1976	24 hr	Radial corridor to CBD Access ramps at 3 locations 3 bus stations including 1,000-car park-ride at outer terminus
I-66 Northern Virginia	1984-expected	9.6 mi	All peak direction lanes of 4-lane freeway	3 or more per vehicle	a.m. and p.m. peak periods	Radial corridor to CBD access ramps at 4 locations along route

Table 4.8. Characteristics of contraflow HOV lanes on grade-separated facilities

Lane Characteristics	New Jersey	Boston	New York	Marin County (California)	Texas
Route	I-495 approach to Lincoln Tunnel	Southeast Expressway	I-495 Long Island Expressway	U.S. 101	I-45
Length in miles	2.5	8	2	4	9.6
Year started	1971	1972	1972	1972	1979
a.m./p.m.	a.m.	a.m.	a.m.	p.m.	a.m., p.m.
Remaining traffic lanes	2	2	2	2	3 or 4
Buffer lane	No	No	No	Yes	No
Typical bus volumes	500/peak hr 900/peak period	35/peak hr 70/peak period	120/peak hr 200/peak period	70/peak hr 150/peak period	N/A 60/peak period (200 vanpools)
Typical passenger volumes	21,000/peak hr 35,000/peak period	1,400/peak hr 3,000/peak period	6,000/peak hr 10,000/peak period	3,000/peak hr 6,000/peak period	N/A 8,000/peak period

Source: Reference (*137*)

Figure 4.31. Shirley Highway (I-95) HOV express lanes in Washington D.C. (middle lanes are reserved exclusively for buses and carpools)

Source: Reference (*134*)

through construction or restriping ("add-a-lane"), or by preempting an existing normal-use lane ("take-a-lane"). Experience with a take-a-lane projects has revealed significant public opposition, as in the case of the diamond

Table 4.9. Characteristics of concurrent flow HOV lanes on grade-separated facilities

Facility	Year Opened	Length	Lane Configuration	Priority Rule	Hours of Operation	Comments
San Francisco (California) Oakland Bay Bridge Approach	1970	0.5 mi	3 lanes taken from 17 at toll plaza; 1 lane taken from 6 upstream	Bus only, 1970; 3 or more per car, 1971	6-9 a.m. inbound; 2-6 p.m. outbound	Queue jumper at toll plaza; free passage through toll plaza without stopping
San Francisco (California) U.S. 101	1974	3.8 mi	1 lane added to 3	Bus only, 1984; 3 or more per car, 1976	6-9 a.m. inbound; 4-7 p.m. outbound	Outbound lane is extension of 4-mi bus-only contraflow lane; free tolls on Golden Gate Bridge
Honolulu-Moanalua	1974	2.7 mi inbound 1.4 mi outbound	1 lane added to 2	4 or more, changed to 3 or more	All day, both directions	Low bus volumes
Boston (Massachusetts) I-93	1974	0.8 mi	1 lane taken from 3	3 or more	6:30-9:30 a.m.	Basically a queue jumper at interchange lane lines
San Diego (California) Route 163	1975	0.5 mi outbound from CBD	1 lane taken from 4	Bus only	3-6 p.m.	Queue jumper upstream of freeway merge area bottleneck; additional 0.4 mi on surface street
Portland (Oregon) Banfield Freeway	1975	3.3 mi inbound 1.7 mi outbound	1 lane added to 2	3 or more	All day, changed: 6-10 a.m. inbound 3-7 p.m. outbound	Emergency turnouts at 2,000-ft intervals
San Francisco (California)	1975	2 mi	1 lane added to 3	3 or more	All day	Queue jumper at 4-lane to 3-lane drop
Miami I-95	1975	7.5 mi	1 lane added to 3	3 or more, changed to 2 or more	7-9 a.m. inbound 4-6 p.m. outbound. (Originally 6-10 a.m., 3-7 p.m.)	2,200 per park-ride lot at outer end connected by exclusive bus ramp
New York City Brooklyn Queens Expressway	1976	1.2 mi	1 lane added to 2	Bus and taxi	7-10 a.m.	Queue jumper upstream of freeway merge area
Los Angeles (California) Santa Monica Freeway	1976	12.6 mi	1 lane taken from 4 or 5	3 or more	6:30-9:30 a.m. 3-7 p.m.	Extensive priority ramp metering also used; terminated by court order after 5 months
New Jersey I-95 George Washington Bridge Approach	1976	0.25 mi	1 lane added to right shoulder	Bus only	Morning peak	Queue jumper at toll plaza
Seattle (Washington) SR 520	1973	1.8 mi	1 lane (right shoulder) added to 2	3 or more, changed from buses only	6:30-9:30 a.m.	Crosses 1 on-ramp and 2 off-ramps

lane on the Santa Monica Freeway. By contrast, public acceptance of add-a-lane projects has been high, even in cases where lane width standards had to be compromised. The primary problem of concurrent-flow lanes is enforcement (*134*). Violating vehicles have virtually unrestricted access to the lane, and positioning enforcement officers at proper locations is difficult, creating the need for a special enforcement plan. Table 4.9 summarizes the general characteristics of selected concurrent-flow HOV projects.

Metered Ramp Bypass. Whenever entrance ramp metering is in effect, it is possible to provide bypass lanes so that buses, vanpools, and carpools avoid any delay associated with ramp queues while still maintaining uncongested flow on the freeway. Los Angeles has a large number of such bypass lanes (Figure 4.34), with over 350 in use (*135*). Minneapolis is the only other area that has made extensive use of the freeway entrance ramp bypass (Figure 4.33).

Exclusive Ramps. Dedication of ramps for exclusive HOV use has generally been limited to special situations. Ramps in New York (I-495), Washington, D.C. (Shirley Highway), Los Angeles (El Monte Busway), and Miami (I-95) are integral parts of freeway priority-lane projects. The Los Angeles and Miami exclusive ramps provide direct connection for HOV's between priority lanes and park-and-ride lots. In Seattle, Washington, exclusive ramps in the CBD are provided for buses and carpools entering the mixed-mode reversible center roadway of the I-5 freeway (Figure 4.35). In Houston, exclusive connections to authorized vehicle lanes have been provided.

Guidelines for Implementation

Guidelines for the implementation of HOV lanes have been formulated by ITE Committee 6A-16. Although currently in a review and revision process, these guidelines are worthy of consideration. Offered are a series of general guidelines and then specific guidelines for surface streets and freeways. The specific suggestions with application for freeways include the following (*136*):

- The potential for HOV lanes on controlled-access highways is limited to high-volume urban corridors.
- Projected corridor demand during the peak periods should indicate potentially serious capacity problems.
- The corridor should be of sufficient length to provide the potential for large time savings to users of HOV lanes.
- Transit bus demand should exist in the corridor.
- Separate HOV roadways should have at least two lanes.
- Contraflow lanes should be restricted to use by professional (or trained) drivers.
- Concurrent-flow lanes should only be considered when a capacity increase is possible, e.g., add-a-lane.
- Access to HOV lanes should be carefully considered.
- For safety and operational reasons, HOV regulations should be strictly enforced.
- It is important to provide facilities to accommodate enforcement vehicles. This need should be addressed during the planning and design stage — not as an operational afterthought.

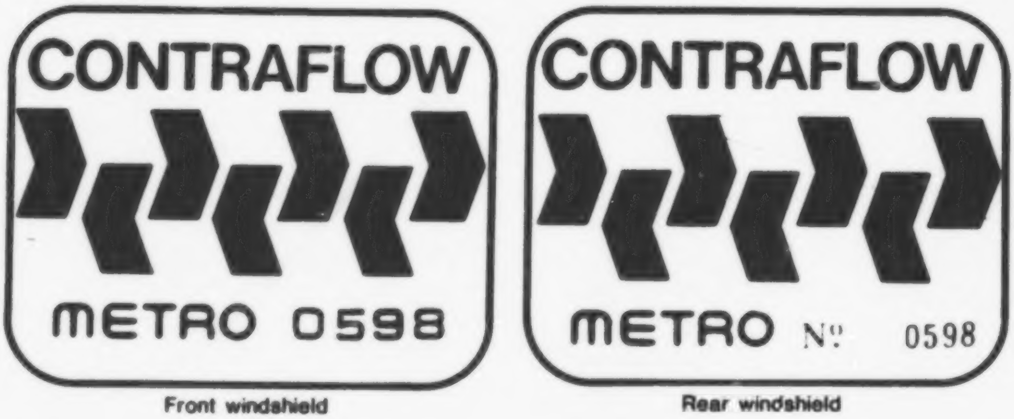


Figure 4.32. Authorized vehicle decal

153

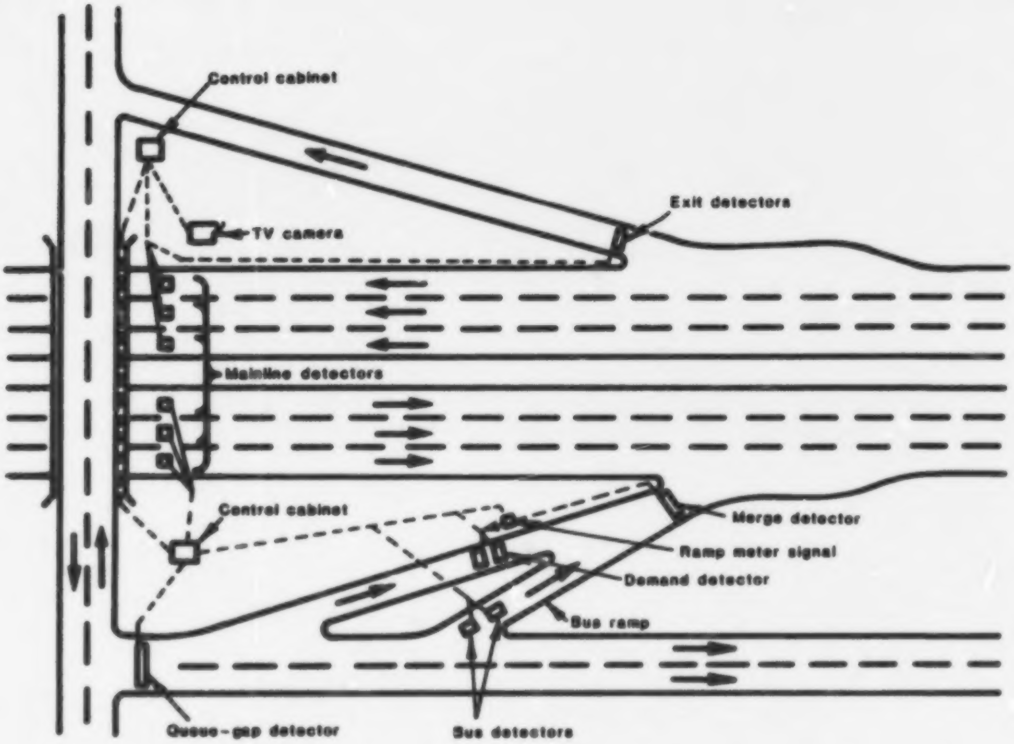

Control cabinet
Exit detectors
TV camera
Mainline detectors
Control cabinet
Merge detector
Ramp meter signal
Demand detector
Bus ramp
Queue-gap detector
Bus detectors

Figure 4.33. Typical ramp metering layout with bypass, I-35 W corridor project — Minneapolis (Minnesota)

Source: Reference (*140*)

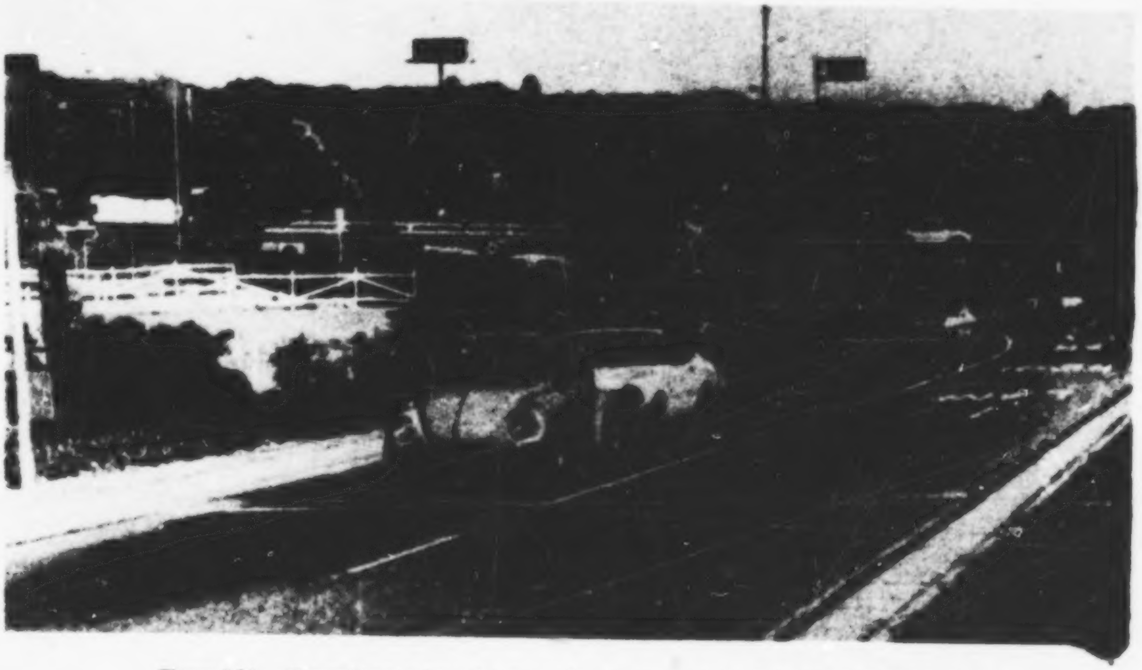


Figure 4.34. Carpool bypass lane at a metered entrance ramp near Los Angeles (California)

Source: Reference (*136*)

Figure 4.35. Overhead electronic changeable message sign on I-5. Seattle (Washington)

REFERENCES

1. Arceneaux, James L., and Basil Mikhalkin. *Inventory of Freeway Geometric Bottleneck Congestion*. Final Report. Freeway Operation Department, District 7, California Division of Highways, May 1973.

2. Biggs, R. G., and Musa J. Misleh. *I.P.E. 408, U.S. 59 (Southwest Freeway) in Houston Control 27-13*. Texas Highway Department, Houston, Texas, October 1971.

3. McDermott, Joseph M., et al. *Chicago Area Expressway Surveillance and Control: Final Report*. Illinois Department of Transportation, Bureau of Materials and Physical Research, Oak Park, Illinois, FHWA Report No. FHWA-IL-ES-27, March 1979.

4. Moskowitz, K. "Research on Operating Characteristics of Freeways." *Institute of Traffic Engineers Proceedings*, 1956, pp. 85-110.

5. Keese, C. J.; Charles Pinnell; and W. R. McCasland. "A Study of Freeway Traffic Operation." *Highway Research Board Bulletin 235*, 1960, pp. 73-132.

6. Wohl, Martin, and Brian V. Martin. *Traffic System Analysis for Engineers and Planners*. McGraw-Hill Book Company, Inc., New York, 1967.

7. Drew, Donald R. *Traffic Flow Theory and Control*. McGraw-Hill Book Company, Inc., New York, 1968.

8. Kahn, David, and Ronald Mintz. *Freeway Traffic Flow Following a Lane Blockage*. Report No. DOT-TSC-FHWA-73-1, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1971; available from NTIS as PB-222-399.

9. Newman, Leonard, and Karl Moskowitz. "Effect of Grades on Service Volume." *Highway Research Record 99*, 1965, pp. 224-243.

10. American Association of State Highway Officials. *A Policy on Design Standards: Interstate System*. American Association of State Highway Officials, Washington, D.C., 1967.

11. *Interim Materials on Highway Capacity*. Transportation Research Circular Number 212, Transportation Research Board, January 1980, ISSN 0097-8515.

12. Treiterer, Joseph. "Traffic Control Characteristics of Urban Freeways." Presented at the International Road Federation World Meeting, Munich, October 1973, pp. 14-20.

13. Crane, Herbert L. *Formation of the Detroit Freeway Operations Unit*. Report TSD-TR-119-69, Department of State Highways, Traffic and Safety Division, State of Michigan, June 1969.

14. Goolsby, M. E. "Influence of Incidents on Freeway Quality of Service." *Highway Research Record 349*, 1971, pp. 41-46.

15. Murphy, Richard J. *A Program to Upgrade and Control the Los Angeles Freeway Network*. Division of Highways, District 7, California Transportation Agency Department of Public Works, July 1970.

16. *Federal Register*, Vol. 48, No. 233, Friday, December 2, 1983.

17. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S. Department of Transportation, Federal Highway Administration, 1978.

18. Pinnell, Charles; Donald R. Drew; William R. McCasland; and Joseph A. Wattleworth. "Evaluation of Entrance Ramp Control on a Six-Mile Freeway Section." *Highway Research Record 157*, 1967, pp. 22-76.

19. Newman, Leonard, Alex M. Dunnett, and Gerry J. Meis. "Evaluation of Ramp Control on the Harbor Freeway in Los Angeles." *Highway Research Record 303*, 1970, pp. 44-55.

20. *Hanshin Expressway Traffic Control System*. Osaka Management Division, Hanshin Expressway Public Corporation, Osaka, Japan, March 1973.

21. *Traffic Control of Metropolitan Expressway*. Metropolitan Expressway Public Corporation, Tokyo, Japan, May 1973.

22. Wattleworth, Joseph A.; Kenneth G. Courage; and James D. Carvell. *An Evaluation of Two Types of Freeway Control Systems*. Report 488-6, Texas Transportation Institute, College Station, 1968.

23. Newman, Leonard; Alex Dunnet; and Gerry Meis. *Freeway Ramp Control — What It Can and Cannot Do*. Freeway Operation Department, District 7, California Division of Highways, February 1969.

24. McCasland, William R. *Freeway Ramp Control System*. Report 24-26F, Texas Transportation Institute, College Station, 1969.

25. Institute of Transportation Engineers, Technical Committee 4M-11. "Displays for Metered Freeway Entrance Ramps." *ITE Journal*, Vol. 54, No. 4, April 1984, pp. 14-18.

26. Masher, D. P., et al. "Guidelines for Design and Operation of Ramp Control Systems." *NCHRP Project 3-22 Final Report*, December 1975. (Loan copy available on request to NCHRP.)

27. Everall, Paul F. *Urban Freeway Surveillance and Control: The State of the Art*. Department of Transportation, Federal Highway Administration, Washington, D.C., November 1972.

28. Breiman, Leo. "A Case Study — LAAFSCP." Paper presented at the Urban Freeway Surveillance and Control Short Course, Technology Service Corporation, Bethesda, Maryland, March 1974.

29. Wagner, Frederick A. *Traffic Control System Improvements: Impacts and Costs*. Federal Highway Administration, Office of Highway Planning, Report No. FHWA-PL-80-005, March 1980.

30. Courage, Kenneth. "Freeway Surveillance and Control: A State of the Art Summary." Paper presented at the Computer Traffic Control Workshop, University of Minnesota, March 20-22, 1974.

31. Drake, Joseph S.; Joseph L. Schofer; and Adolf D. May, Jr. "A Statistical Analysis of Speed Density Hypotheses." *Highway Research Record 154*, 1967, pp. 53-87.

32. Drew, Donald R.; Lynn R. LaMotte; Joseph A. Wattleworth; and Johann H. Buhr. "Gap Acceptance in the Freeway Merging Process." *Highway Research Record 208*, 1967, pp. 1-36.

33. Buhr, Johann H.; William R. McCasland; James D. Carvell; and Donald R. Drew. "Design of Freeway Entrance Ramp Merging Control Systems." *Highway Research Record 279*, 1969, pp. 137-149.

34. Drew, Donald; William R. McCasland; Charles Pinnell; and Joseph A. Wattleworth. *The Development of An Automatic Freeway Merging Control System*. Research Report 24-19, Texas Transportation Institute, College Station, 1966.

35. Wattleworth, Joseph A., and Donald S. Berry. "Peak-Period Control of a Freeway System — Some Theoretical Investigations." *Highway Research Record 89*, 1965, pp.15-20.

36. May, Adolf D., Jr. "Peak-Period Analysis and Control of a Freeway System." *Highway Research Record 157*, 1967, pp. 15-20.

37. Courage, Kenneth F., and Moshe Levin. *A Freeway Corridor Surveillance Information and Control System*. Research Report 438-8, Texas Transportation Institute, College Station, December 1968.

38. Messer, Carroll J. "Development and Evaluation of a Multi-Level Freeway Control System for the Gulf Freeway." Paper presented to the Freeway Operations Committee, 50th Annual Meeting of the Highway Research Board, Washington, D.C., 1971.

39. Looze, D. P., et al. "On Decentralized Estimation and Control with Application to Freeway Ramp Metering." *IEEE Transactions on Automatic Control*, Vol. AC-23, No. 2, April 1978, pp. 268-275.

40. Blumentritt, C. W., et al. "Guidelines for Selection of Ramp Control Systems." *NCHRP Report 232*, May 1981.

41. Allen, T. M.; H. Lunefield; and G. J. Alexander. "Driver Information Needs." National Cooperative Highway Research Program Report 123, Washington, D.C., 1971.

42. Dudek, Conrad L., and Hal B. Jones. "Evaluation of Real-Time Visual Information Displays for Urban Freeways." *Highway Research Record 366*, 1971, pp. 64-78.

43. Wattleworth, Joseph A., Kenneth G. Courage, and James D. Carvell. *An Evaluation of Two Types of Freeway Control Systems*. Report 4888-6, Texas Transportation Institute, College Station, 1968.

44. Burford, Wesley M., III. *A Study of Effectiveness of a Changeable Message Sign System*. Department of Civil Engineering, University of Texas at Austin, January 1983.

45. Klijnhout, J. J. *Motorway Control and Signalling System*. Ministerie Van Verkeer en Waterstaat, November 1982.

46. Ranahauer, Adolf, and Erich Abel. "The First Remote-Controlled Traffic Sign and Signal System Designed for Use Along Highways." *Siemens-Zeitschriff*, Vol. 39, June 1965, pp. 682-690.

47. LePera, R., and R. Nenzi. "TANA — An Operating Surveillance System for Highway Traffic Control." *IEEE Proceedings*, Vol. 61, No. 5, May 1973, pp. 542-556.

48. Payne H. J., and A. D. May. *Control of Mainline Freeway and Freeway — Freeway Connectors for Bottleneck Alleviation*. Report No. FHWA/RD-82/030, U.S. Department of Transportation, Federal Highway Administration, June 1982. (Final Report.)

49. Pinnell, Charles, and Donald G. Cappelle. "Operational Study of Signalized Diamond Interchanges." *Highway Research Board Bulletin 324*, 1962, pp. 38-72.

50. Love, P., et al. *Integrated Motorist Information System (IMIS) Feasibility and Design Study*. Sperry Rand Corporation, May 1978. (See also FHWA-RD-78-23 and 24.)

51. Urbanek, G. L., and R. W. Rogers. *Alternative Surveillance Concepts and Methods for Freeway Incident Management*. Volume 1 — Executive Summary, Report No. FHWA-RD-77-58, Federal Highway Administration, Offices of Research and Development, Washington, D.C., March 1978.

52. Kahn, Robert. *Interim Report on Incident Detection Logics for the Los Angeles Freeway Surveillance and Control Project*. Freeway Operation Department, District 7, Department of Transportation, California Division of Highways, September 1972. (Unpublished Report.)

53. Courage, Kenneth G., and Moshe Levin. *A Freeway Corridor Surveillance, Information and Control System*. Research Report 488-8, Texas Transportation Institute, College Station, December 1968.

54. Cook, A. R., and D. E. Cleveland. "Detection of Freeway Capacity — Reducing Incidents by Traffic Stream Measurements." *Transportation Research Record 495*, 1974, pp. 1-11.

55. Dudek, C. L.; C. J. Messer; and N. B. Nuckles. "Incident Detection on Urban Freeways.' *Transportation Research Record 495*, 1974, pp. 104-107.

56. Payne, H. J., and S. C. Tignor. "Freeway Incident Detection Algorithms Based on Decision Trees with States." *Transportation Research Record 682*, 1978, pp. 30-37.

57. Ahmed, S. A., and A. R. Cook. "Time Series Models for Freeway Incident Detection." *Transportation Engineering Journal of the ASCE*, Vol. 106, No. TE6, 1980, pp. 731-745.

58. Willsky, A. S., et al. "Dynamic Model-Based Techniques for the Detection of Incidents on Freeways." *IEEE Transactions on Automatic Control*, Vol. AC-25, No. 3, 1980, pp. 347-360.

59. Sakasita, M., and A. D. May. "Development and Evaluation of Incident-Detection Algorithms for Electronic-Detector Systems on Freeways." *Transportation Research Record 533*, 1975, pp. 48-63.

60. Whitson, R. H., et al. "Real-Time Evaluation of Freeway Quality of Traffic Service." *Highway Research Record 289*, 1969, pp. 38-50.

61. Ahmed, S. A., and A. R. Cook. "Application of Time Series Analysis Techniques to Freeway Incident Detection." *Transportation Research Record 841*, 1982, pp. 19-21.

62. Tignor, S. C., and H. J. Payne. "Improved Freeway Incident Detection Algorithms." *Public Roads*, Vol. 41, No. 1, June 1977, pp. 32-40.

63. Levin, M., and G. J. Krause. "Incident-Detection Algorithms, Part 1. Off-line Evaluation." *Transportation Research Record 722*, 1979, pp. 49-58.

64. Levin, M., G. M. Krause, and J. A. Budrick. "Incident-Detection Algorithms, Part 2. On-Line Evaluation." *Transportation Research Record 722*, 1979, pp. 58-64.

65. Summer, R., et al. *Freeway Management Handbook*. Department of Transportation, Federal Highway Administration, May 1983. (Four-volume set.)

66. McCasland, William R. *Optimizing Flow in an Urban Corridor*. Dallas Annual Report 1970-1971. Texas Transportation Institute, College Station, 1971.

67. Goolsby, Merrell E., and W. R. McCasland. *Freeway Operations on the Gulf Freeway Ramp Control System*. Report 24-25, Texas Transportation Institute, College Station, 1969.

68. Weinberg, Morton I.; Normal J. Deleys; and Richard F. Schneeberger. "Surveillance Methods and Ways and Means of Communicating with Drivers." *National Cooperative Highway Research Program Report 28*. Highway Research Board, Washington, D.C., 1966.

69. *Los Angeles Area Freeway Surveillance and Control Project*. Third Annual Report. Department of Public Works, State of California, Sacramento, February 1973.

70. *Motorist Aid Systems*. National Cooperative Highway Research Program, Synthesis of Highway Practice. Highway Research Board, Washington, D.C., 1971.

71. Michigan Department of Transportation. Personal correspondence with Mr. G. F. Paesani, Acting Supervising Engineer, MDOT, Freeway Operations Unit, May 1983.

72. Spica, F. M. *Project BEAR One Year Evaluation.* Michigan Department of State Highways and Transportation, December 1980.

73. Ritch, G. P., and J. L. Buffington. *Analyzing the FREQ3CP Freeway Operations Simulation Model.* Research Report 210-3, Texas Transportation Institute, October 1978.

74. McDermott, J. M. "Surveillance and Control For Incidents On Chicago Area Freeways." Paper prepared for presentation at the 1974 Transportation Research Board Mid-Year Meeting (Technical Session on Better Management of Traffic Incidents), Jacksonville, Florida, August 5-7, 1974.

75. Green, Richard H. *The 42-Mile Freeway Surveillance Loop.* Freeway Operation Department, District 7, California Division of Highways, 1973.

76. Urbanek, G. L., and S. C. Tignor. "Methodology for Evaluation of Alternative Low-Cosc Freeway Incident Management Techniques." *Transportation Research Record 682.* 1978, pp. 103-105.

77. Urbanek, G. L.; S. C. Tignor; and G. C. Price. "Results of Implementing Low-Cost Freeway Incident Management Techniques." *Transportation Research Record 722,* 1979, pp. 91-97.

78. DeRose, F. "Lodge Freeway Traffic Surveillance and Control Project." *Highway Research Record 21,* 1963, pp. 69-89.

79. Gervais, E. E. "The John Lodge Freeway Surveillance System." *Traffic Engineering,* Vol. 32, No. 10, 1957.

80. Hilbert, E. Carl, et al. *Wide Area Detection System — Conceptual Design Study.* FWHA-RD-77-86, February 1978.

81. Richard, C. L., and K. Bushnell. "Television Equipment for Traffic Surveillance." *Highway Research Record 10,* 1963, pp. 47-76.

82. McCasland, William R. "Application of Closed Circuit Television for Traffic Surveillance in Texas." Texas Transportation Institute, Research Report 139-11, August 1971.

83. Hsy, Y. S., and P. K. Munjal. "Freeway Digital Simulation Models." *Transportation Research Record 509,* 1974, pp. 24-41.

84. Richard, R. M.; R. L. Baker; and W. P. Sheldon. "Simulation of Traffic Flow as a Basis for Interchange Design." Arizona Transportation and Traffic Institute, for Arizona Highway Department and Federal Highway Administration, June 1965. (Final Report.)

85. Kobett, D. R. *A Digital Simulation Model of Freeway Traffic,* Volume I — "Model Description." Final Report, Midwest Research Institute, Contract CPR-11-3661 for Federal Highway Administration, December 1968.

86. Kobett, D. R., and S. L. Levy. "Study of Expressway Traffic Flow Through Digital Simulation." Midwest Research Institute, Contract CPR-11-0963 for Federal Highway Administration, May 1965. (Final Report.)

87. St. John, A. D.; D. R. Kobett; D. Sommerville; and W. D. Colanz. *Traffic Simulation for the Design of Uniform Service Roads in Mountainous Terrain,* Vol. I-IV. Midwest Research Institute, Contract CPR-11-5093 for Federal Highway Administration, May 1970. (Final Report.)

88. Worral, R. D., and A. G. R. Bullen. "Lane-Changing on Multi-Lane Highways." Northwestern University, Contract CPR-11-5228 for Federal Highway Administration, August 1969. (Final Report.)

89. Sinha, K. C. "The Development of a Digital Simulator for the Analysis of Freeway Traffic Phenomena." University of Connecticut, 1969. (Doctoral Dissertation.)

90. Sinha, K. C., and R. F. Dawson. "The Development and Validation of a Freeway Traffic Simulator." *Highway Research Record 308,* 1970, pp. 34-47.

91. Leland, S. D. "A General Traffic Flow Simulation Model for Freeway Operation." Connecticut Department of Transportation, May 1970. (Final Report.)

92. Buhr, J. H.; T. C. Meserole; and D. R. Drew. "A Digital Simulation Program of a Section of Freeway with Entrance and Exit Ramps." *Highway Research Record 230,* 1968, pp. 15-31.

93. Nemeczky, J. A., and B. D. Widdice. "Development and Validation of a Digital Simulation Model for Research in Geometric Design and Control of Diamond Interchanges." Presented at the Summer Simulation Conference Sponsored by ACM/SHARE/SCI, 1970.

94. Warnshuis, Paul. "Simulation of Traffic Flows Through Interchange Systems of Arbitrary Configuration." System Development Corp., Contract FH-11-7628 for Fedreal Highway Administration, March 1972.

95. Mikhalkin, B. "Estimation of Roadway Behavior Using Occupancy Detectors." University of Southern California, February 1971. (Doctoral Dissertation.)

96. Wildermuth, Bruno R. "Effect of Lane Placement and Truck Traffic Freeway Flow Characteristics." Wilbur Smith and Associates for Georgia Highway Department, Project 6909, April 1971. (Final Report.)

97. Wicks, David. *Traffic Flow Simulation Study: The SCOT Model*, Vol. I-IV. Final Report, General Applied Science Laboratories, Inc., Contract DOT-TSC-161, February 1972.

98. Blankenhorn, R. C., and A. D. May. "FREQ2: A Revision of the 'FREQ' Freeway Model." Institute of Transportation and Traffic Engineering, University of California, Berkeley, June 1972. (Special Report.)

99. May, A. D.; R. D. Minister; L. P. Lew; and K. Ovaici. "A Computer Simulation Model for Evaluating Priority Operations on Freeways." Institute of Transportation and Traffic Engineering, University of California, Berkeley, Contract FH-11-7704 for FHWA, June 1972. (Special Report.)

100. Payne, H. J. "Aggregate Variable Models of Freeway Traffic." Department of Electrical Engineering, University of Southern California, National Science Foundation Grant GK-24520, June 1972.

101. Harju, G. W.; L. R. Bush; R. F. Kramer; and H. S. Porges: "An Advanced Computer Concept for Freeway Traffic Flow Modeling." Presented at the Summer Simulation Conference, June 1972.

102. May, A. D. "Freeway Corridor Analysis." Presented at Conference on the Application of Traffic Simulation Models, June 3-5, 1981, Williamsburg, Virginia.

103. Makigami, Y., and W. L. Woodie. "Freeway Travel Time Evaluation Technique." *Highway Research Record 321*, 1970, pp. 149-161.

104. Brown, G. H. J., and R. S. Scott "Micro-Assignment: A New Tool for Small-Area Planning." *Highway Research Record 322*, 1970, pp. 149-161.

105. Yagar, S. "CORQ — A Model for Predicting Flows and Queues in a Road Corridor." *Transportation Research Record 533*, 1975, pp. 77-87.

106. Yagar, S. "An Analysis of the Morning Peak Traffic Problems in the Eastbound Corridor Serving Ottawa." Ontario Ministry of Transportation and Communications, 1973.

107. Yagar, S. "Measures of the Sensitivity and Effectiveness of the CORQ Traffic Model." *Transportation Research Record 562*, 1976, pp. 38-48.

108. Easa, S. M., and B. L. Allen "Analysis of Urban Freeway Corridors: Toward The Development of a Model for Assessing Freeway Control Plans." McMaster University, Interim Report 3311-76/1, July 1976.

109. Easa, S. M., and B. L. Allen. "Analysis of Urban Freeway Corridors: Toward The Development of a Model for Assessing Freeway Control Plans." McMaster University, Final Report 3311-72/2, Vol. 1, March 1977.

110. Allen, B. L., and S. M. Easa. "Analysis of Urban Freeway Corridors: Field Validation of CORCON — A Corridor Model for Assessing Freeway Control Plans." McMaster University, Final Report 3311-77/3, Vol. 2, March 1977.

111. Easa, S. M., and B. L. Allen. "CORCON: Freeway CORridor Assignment and Control Model." Paper presented at the 57th Annual Meeting, Transportation Research Board, 1978.

112. Allen, Brian L.; Said M. Easa; and E. R. Case. "Application of Freeway-Corridor Assignment and Control Model." *Transportation Research Record 682*, 1978, pp. 76-84.

113. Makigami, Y.; L. Woodie; and A. D. May. "Bay Area Freeway Operations Study." Part I of III: *The Freeway Model*. Berkeley: University of California, Institute of Transportation and Traffic Engineering, August 1970. (Final Report.)

114. Blankenhorn, R. C., and A. D. May. "Freeway Operations Study — Phase III." Interim Report No. 4: FREQ2 — A Revision of the FREQ Freeway Model. Berkeley: University of California, Institute of Transportation and Traffic Engineering, June 1972.

115. Stock, W. A.; R. C. Blankenhorn; and A. D. May. "Freeway Operations Study — Report III." *Report 73-1: The FREQ3 Freeway Model*. Berkeley: University of California, Institute of Transportation and Traffic Engineering, June 1973.

116. Ovaici, K.; A. D. May; R. F. Teal; and J. K. Ray. "Simulation of Freeway Priorities Strategies (FREQ3CP)." Federal Highway Administration, June 1975. (Final Report.) (Also published in *Proceedings of Sixth International Symposium on Transportation and Traffic Theory*, Sydney, Australia, August 1974; *Transportation Research Record 533*, 1975; and available as UCB Doctoral Dissertation.)

117. Eldor, M., and A. D. May. "Freeway Operations Study — Phase III." *Report 73-1*. Cost Effectiveness Evaluation of Freeway Design Alternatives. Berkeley: University of California, Institute of Transportation and Traffic Engineering, June 1973. (Also published in *Proceedings of Engineering Optimization Conference*, Liverpool, England, August 1974; and in *Highway Research Record 495*, 1975.)

118. Wang, J. J., and A. D. May. "Freeway Operations Study — Phase III." *Report 73-3, Analysis of Freeway On-Ramp Control Strategies*. Berkeley: University of California, Institute of Transportation and Traffic Engineering, June 1973. (Also published in *Highway Research Record 469*, pp. 16-25, 1973; and available as UCB Doctoral Dissertation.)

119. Jovanis, P. P.; A. D. May; and W. Yip. "FREQ6PE — A Freeway priority Entry Control Simulation Model." California Department of Transportation, Final Report, September 1978, approximately 300 pages. (Vol. II is for limited distribution and contains computer-related materials.)

120. Cilliers, T.; A. D. May; and R. Cooper. "FREQ6PL — A Freeway Priority Lane Simulation Model." California Department of Transportation, Final Report, September 1978. (Vol. II is for limited distribution and contains computer-related materials.) (Presented to Transportation Research Board for possible presentation and publication, January 1979. Also available as UCB Doctoral Dissertation.)

121. Roden, D. B.; W. Okitsu; and A. D. May. *FREQ7PE — A Freeway Corridor Simulation Model*. Institute of Transportation Studies, University of California, Berkeley, June 1980.

122. Wicks, D. A., and B. J. Andrews. "Development and Testing of INTRAS, a Microscopic Freeway Simulation Model." Vol. 2 — User's Manual. FHWA-RD-80-107, July 1980. (Final Report.)

123. Peat, Marwick, Mitchell & Co., and KLD Associates, Inc. "Network Flow Simulation for Urban Traffic Control System — Phase II." Report No. DOT-FH-11-7885, 1973.

124. Payne, H. J., and D. C. Young. "MACL: A Macroscopic Simulation Model of Freeway Traffic" (Version II). Orincon Corp., April 1977.

125. Payne, H. J., and H. M. Koble. *A Comparison of Macroscopic and Microscopic Simulation Models (MACK and INTRAS)*. Orincon Corp., Report OC-R-78-11-9367-1, March 31, 1978.

126. Lieberman, E. B., and D. A. Wicks. "Traffic Flow Simulation Study — The SCOT Model." *Highway Research Record 409*, Washington, D.C., 1972, pp. 34-45.

127. Reiss, R. A. *Traffic Diversion Software-Applications Summary*, Report FHWA/RD-80/100, U.S. Department of Transportation, Federal Highway Administration, September 1981.

128. *Final Design Report — Diversion of Intercity Traffic at a Single Point*. Sperry Systems Management, September 1974.

129. *Description of Sperry Traffic Analysis and Research (STAR) Simulation Program*. Sperry Systems Management, October 1974.

130. Berger, C. R., et al. "Single Point Diversion of Freeway Traffic." Presented at the 55th Annual Meeting, Transportation Research Board, January 1976.

131. Rothenberg, Morris J., and Donald R. Samdahl. *High Occupancy Vehicle Facility Development, Operation and Enforcement*. U. S. Department of Transportation, Federal Highway Administration, Implementation Package FHWA-IP-82-1, April 1982.

132. Fuhs, Charles A. *Concurrent Flow HOV Treatment on Freeways, A Success Story in Houston*. Metropolitan Transit Authority of Harris County, Project Development Report 81-7, August 1981.

133. Taube, Robert N., and Charles A. Fuhs. "Houston's I-45 Contraflow Transit Project." *Transportation Research Record 798*, 1981.

134. Roark, John J. *Enforcement of Priority Treatment for Buses on Urban Streets*. National Cooperative Transit Research Board, Synthesis of Transit Practice No. 2, May 1982.

135. *Evaluation of Preferential Lanes for HOV's at Metered Ramps*. U. S. Department of Transportation, Federal Highway Administration, FHWA/RD-82/121, November 1982. (As prepared by Caltrans.)

136. "Guidelines for High-Occupancy Vehicle (HOV) Lanes." *ITE Journal*, Vol. 52, No. 2, February 1982, pp. 30-33.

137. McDermott, Joseph M.; Stephen J. Kolenko, and Robert J. Wojcik. *Chicago Area Expressway Surveillance and Control: Final Report*. Expressway Surveillance Report No. 27. Bureau of Materials and Physical Research, Illinois Department of Transportation, Springfield, March 1979.

138. Review Comments by Edward B. Lieberman, KLD Associates, on *Traffic Control Systems Handbook*, Federal Highway Administration, U.S. Department of Transportation, 1976, p. 16.

139. "Freeway Lanes For High-Occupancy Vehicles." December 1973, p. 15.

140. Wolsfeld, Richard P.; Glen C. Carlson; and Robert J. Benke. "Moving People on the I-35W Corridor." *Traffic Engineering*, Vol. 43, No. 11, August 1973, pp. 45-49.

5. DETECTORS

CONTENTS

Section *Page*

5.1 INTRODUCTION 5.3

5.2 TYPES OF DETECTORS 5.3
- **Inductive Loop Detector (ILD)** 5.3
  - ***Loop Characteristics*** 5.4
  - ***Loop Electronics*** 5.5
- **Magnetic Detector** 5.6
  - ***Probe Characteristics*** 5.6
- **Magnetometer Detector** 5.6
  - ***Probe Characteristics*** 5.6
- **Detectors in Early Use** 5.7
  - ***Pressure Detectors*** 5.7
  - ***Radar Detectors*** 5.7
  - ***Sonic Detectors*** 5.8
- **Special-Purpose Detectors** 5.8
  - ***High-Intensity Light Detectors*** 5.8
  - ***Passive Bus Detector*** 5.9
  - ***Environmental Detectors*** 5.9
  - ***Pedestrian Detectors*** 5.9
    - *Pushbutton Detectors* 5.9
    - *Blind and/or Deaf Pedestrian Crossings* 5.9
- **Comparison of Vehicle Detectors** 5.9

5.3 DETECTOR OPERATIONS SUMMARY 5.9
- **Detector-Controller Interrelationship** 5.12
- **Low-Speed Approaches** 5.12
  - ***Locking Detection Memory*** 5.12
  - ***Nonlocking Detection Memory*** 5.12
- **High-Speed Approaches** 5.13

5.4 VEHICLE DETECTOR LOCATION AND CONFIGURATION 5.15
- **Isolated Actuated Intersection Control** 5.15
  - ***Small-Area Detectors*** 5.15
  - ***Large-Area Detectors*** 5.16
  - ***Left-Turn Lanes*** 5.16
  - ***Detection of Small Vehicles*** 5.18
- **System Control** 5.18
- **ILD Applications for System Sensors** 5.19
- **Arterial Street Systems** 5.20
- **Network Control Systems** 5.22
  - ***Selection of Links*** 5.23
    - *First-Generation Control* 5.23
    - *TRSP-Plan Generation Control* 5.23

163

Section *Page*

Lateral Detector Placement 5.24
Longitudinal Detector Position 5.25
First-Generation Control 5.25
TRSP-Plan Generation Control 5.25
General Guidelines for Spotting Detectors 5.26
Freeway Surveillance and Control 5.26
Ramp Metering 5.27
Mainline Detection 5.28
Incident Detection 5.30

5.5 FUTURE DETECTOR TECHNOLOGY 5.31
Self-Powered Vehicle Detector 5.31
Wide Area Detection System (WADS) 5.33

REFERENCES 5.33

164

5. DETECTORS

5.1 INTRODUCTION

The operational efficiency of any traffic-responsive control system depends on its ability to sense the presence of traffic. Traffic sensing is accomplished by a device commonly referred to as a detector. Traffic detection utilizes the following types of detectors:

- Inductive loop
- Magnetic
- Magnetometer
- Pressure
- Radar
- Sonic
- Photocells
- Infrared beam
- Radio frequency
- Pedestrian
- High-intensity light emission
- Environmental

Traffic control deals with the movement of vehicles and pedestrians. Traffic detector unit outputs may be used either singly or in combination to measure variables of presence, volume, speed, and occupancy. Traffic detector surveillance measures can be used as control parameters at individual signalized intersections, in coordinated traffic-responsive signal systems, or for freeway operations.

For example, at an actuated signalized intersection, decisions such as extending the green for a vehicle or assigning the right-of-way to it at the earliest opportunity are based upon detector inputs to the local intersection controller assembly. The local controller unit will process these inputs, compare the processed detector information with some preset control parameter or parameters, and make a decision as to how the intersection control will be phased and timed.

All detectors operate on one of the following detection principles:

- Detecting a mechanical force which has caused the contacts on a switch to close
- Detecting a change in energy caused by the motion or presence of a vehicle

Pressure detectors and pushbuttons are examples of detection by mechanical force. Examples of energy-change detectors are the magnetic, radar, sonic, and inductive loop detectors.

This chapter presents a discussion of the following aspects of traffic detectors:

- Types
- Locations and configurations
- Applications
- Future detector technology

5.2 TYPES OF DETECTORS

This section provides technical information for vehicle and special-purpose detectors used in modern-day traffic control. Although all the detectors previously mentioned have been applied to various forms of traffic control, those most widely used today include (1) inductive loop, (2) magnetic, and (3) magnetometer detectors. For each of these detector types, the theory of operation, the sensitivity characteristics, and the electronic units are discussed, followed by a brief description of earlier detectors. Special-purpose detectors will also be discussed in relation to high-occupancy and emergency vehicles, pedestrians, and environmental conditions.

Inductive Loop Detector (ILD)

The inductive loop detector (ILD) system, as illustrated in Figure 5.1, is currently the most popular vehicle detector for individual signalized intersections, signal systems, and freeway surveillance systems. The ILD system consists of (1) one or more turns of insulated loop wire wound in a shallow slot sawed in the pavement, (2) a lead-in cable from the curbside pull box to the intersection cabinet, and (3) a detector electronics unit housed in an intersection cabinet. The detector electronics unit drives energy through the loop system at frequencies in a normal range of 20 to 200 kHz. The ILD system forms a

165

tuned electrical circuit, of which the loop wire is the inductive element. When a vehicle passes over the loop or is stopped within the loop, it decreases the inductance of the loop. This decrease in inductance then actuates the detector electronics output relay or circuit which, in turn, sends an impulse to the controller unit signifying that it has detected the passage or presence of a vehicle.

Loop Characteristics. The sensitivity of detector electronics has been defined as the smallest percent change in total loop inductance (*3*) which can be detected. Many users have specified that loop detector units respond to a 0.02 percent change in inductance at the detector unit. This degree of sensitivity provides some safety margin by offsetting the inductance present in the lead-in cable, but is usually sufficient to detect high-bed trucks and motorcycles.

The National Electrical Manufacturers Association (NEMA), however, has recognized differences in detector unit design by mentioning both delta L and L/L for its test vehicle definition. NEMA specified 3 sizes of motor vehicles in terms of the delta L produced by each. For example, NEMA TS-1 1983 (*1*), specifies that, in order to meet the requirements of the sensitivity test, candidate detector units be capable of detecting any of 3 different-sized vehicles on any of 3 defined loop systems.

Loop detector units operate within a range of inductance. The loop size, number of turns of loop wire, and lead-in length must produce an inductance with a range that is compatible with the design of the detector unit. If the inductance of the loop wire plus the lead-in cable falls outside this range, the detector unit will not operate properly. NEMA specifies that a detector unit must be capable of operating satisfactorily over a range of 50 to 700 microhenries (at 50 kHz) (*1*). Several of the available ILD units operate at much higher inductances when a combination of loops is wired in series. The inductance of a loop can be determined from Table 5.1 (*2*), in which the boundaries show the designs recommended for practical use, but loops as large as 6 ft by 35 ft can have three turns. The inductance of the lead-in is added to the loop inductance, shown in Table 5.1, at the rate of 0.23 microhenries per foot of lead-in.

In the industry, the general standard to keep the inductance within the required range of the detector unit is as follows:

Loop perimeter (ft)	Turns (no.)
Under 30	3
Over 30	2

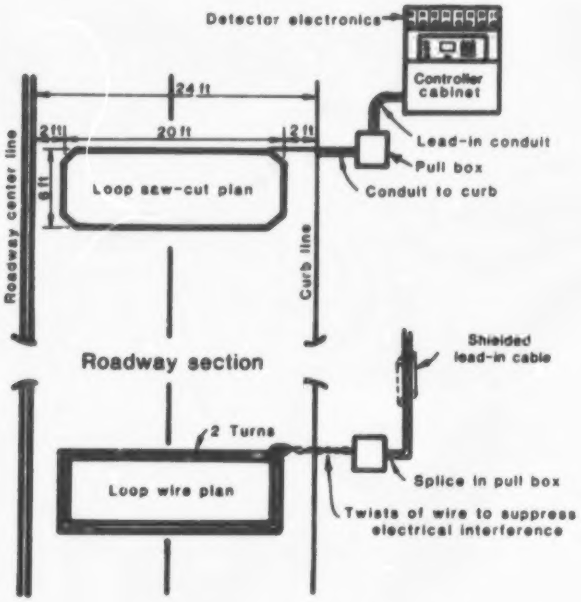

Detector electronics
Controller cabinet
24 ft
2 ft
20 ft
2 ft
6 ft
Loop saw-cut plan
Lead-in conduit
Pull box
Conduit to curb
Roadway center line
Curb line
Roadway section
Shielded lead-in cable
2 Turns
Loop wire plan
Splice in pull box
Twists of wire to suppress electrical interference

Figure 5.1. Principal components of an inductive loop detector system

Table 5.1. Calculated loop inductance in microhenries

Loop Size (Ft)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
5 x 5	9	30	62	104	155		
6 x 6	10	37	78	129	194	269	355
6 x 10	14	51	107	181			
6 x 15	19	69	147	249			
6 x 20	24	88	187	320			
6 x 22	26	96	204	349			
6 x 25	29	107	229	392			
6 x 30	34	126	272	461			
6 x 35	39	146	315	542			
6 x 40	43	165	359	618			
6 x 45	48	185	402	695			
6 x 50	53	205	447	773			
6 x 55	58	225	492	853			
6 x 60	63	245	537	932			
6 x 65	67	265	583	1012			
6 x 70	72	286	628	1092			

Note: Spacing between loop conductors: 150 mm, center to center. Boundaries (shaded areas) show the designs recommended for normal use.

Source: Reference (*2*)

The combination of loops connected together also affects the inductance. A series connection provides a maximum loop magnetic field, and, therefore, the most sensitive configuration when extra-long lead-in cable is used with the loops. Series connections are recommended when the loops are connected to a digital-type detector that operates on changes of inductance (*3*). A user may also reduce the inductance by connecting loops in parallel. Again, care must be exercised to keep that the inductance from falling below the lower operating range of the detector unit. A combination scheme of a series/parallel connection can also be used to maintain an acceptable inductance level.

Loop Electronics. The electronic units which generate the energy and monitor an ILD system have changed considerably since the early 1970s. Modern units are capable of compensating for or tracking drift in the resonant frequency caused by environmental changes in moisture and temperature. The types of electronic design units commonly used today are as follows:

- Analog phase-shift detectors
- Digital frequency-shift detectors
- Digital period-shift detectors

Digital microcircuits can process loop inductance information automatically much faster and with much greater accuracy than analog circuits. The control over memory, the versatile logic, and the ability to manipulate data permit precise control of adapt rates, ensure predictability of sensitivity, threshold accuracy and repeatability, and enable automatic tuning.

The ILD electronic units are relatively inexpensive, selling in 1985 for approximately $75 to $135 per channel of detection. Many of these units provide multichannels of detection (2 or 4). Units are available for shelf-mounting or rack-mounting. Some units offer timing capability on each channel which means that, when selected, the detector output is extended or delayed for the time set. An extension detector connected to a small loop can essentially imitate the output of a normal detector unit connected to a very long loop. Delay detectors are extensively used in detecting congestion and screening out false calls for the green signal. Some of the recent versions have an open-loop diagnostic capability, with a test switch to confirm intermittent connections. With the advent of digital loop detector units to compensate for drift, many states are now using ILD systems as part of their design standards.

As stated previously, NEMA has developed both performance and design requirements of interchangeable ILD units (*1*). However, before selecting a model, a user should consult the recent FHWA *Traffic Detector Handbook* (*3*), which examines several important elements of loop detector units, some of which are not addressed by NEMA standards. In addition, the states of California and New York have developed design requirements for detector electronics used in the Model 170 "Hardware Specification" (*33*), and the Institute of Transportation

167

Engineers (ITE) has developed "A Standard for Vehicle Detectors, Revised Standard" (*34*). Depending on a unit's application, users should review the following factors of ILD electronic units:

- Tuning range
- Loss of detection on long loops during saturated flow
- Loss of sensitivity with increasing length of lead-in cable
- Loss of sensitivity from pavement overlay
- Pulse-mode reset
- Response time
- Recovery from sustained occupancy
- Failsafe operation with loops that are grounded, open, or shorted
- Lightning damage and other electrical interference
- Delay/extension control
- Cabinet space

Magnetic Detector

Magnetic detectors were one of the early forms of vehicle detection devices. They are still being used today where deteriorated pavements and frost activity tend to break the loop wire of the ILD or or where it desirable to install detection without cutting the pavement. Magnetic detectors operate on the basis of a change in the lines of flux from the earth's magnetic field. A coil of wire with a highly permeable core is placed below the surface of a roadway. When a metallic object such as a vehicle comes near to or passes over the coil, the constant lines of flux passing through the coil are deflected by the vehicle, thus causing a voltage to be induced in the coil. A high-gain amplifier then enables this voltage to operate a relay, which sends a message to the controller unit that a vehicle has been detected.

Figure 5.2 illustrates a magnetic detector (probe) that is tunnelled under the roadway and protected in a nonconducting waterproof material. Normally, a magnetic detector can be used to detect from one to three lanes of traffic, depending on the sensitivity setting of the amplifier relay assembly. The type of magnetic detector illustrated in Figure 5.2 is nondirectional; i.e., it cannot distinguish between vehicles traveling in an opposite direction.

Probe Characteristics. Since a magnetic detector is a passive device which does not create a field around it, vehicles must be in motion through the zone of influence to create a call to the controller unit. Therefore, theoretically this type of detector is not suitable for applications where vehicle-presence detection is required, because at very low speeds (less than 3 to 5 mph) a usable signal may not be generated. Typical applications of magnetic detectors are for high-speed approaches where small-area detection is combined with locking memory on the controller unit phase, for areas with poor pavement conditions where the previous installation of loop detectors has been unsuccessful.

Two types of magnetic detectors available include one which is installed flush with the pavement (surface mount), and the other 12 to 30 in. below the pavement (subsurface mount), as shown earlier.

While magnetic detectors are inexpensive, reliable, and simple, they are suitable only for pulse output in traffic-actuated signal control and traffic volume counting.

Magnetometer Detector

The magnetometer detector operates by sensing a change in the vertical component of the earth's magnetic field caused by the presence or passage of a vehicle is over a magnetic probe installed within the pavement. A voltage change is sensed when a vehicle over the probe, thus causing the closure of the output relay in the electronic unit. Vehicles traveling at speeds from 0 to 100 mph are detected. A magnetometer detector system, as illustrated in Figure 5.3, consists of the probe, probe cable, lead-in cable, and the electronic unit.

Magnetometer detectors provide an alternative for the induction loop detector (ILD) in several applications. However, this detector is used primarily to provide vehicle-counting and passage information at individual intersections, where the device senses a vehicle in a small area. A large-area presence-detection application requires a series of probes, which is more costly than the ILD system. Magnetometers may be used under bridge decks when damage to the reinforcing steel is a concern, or in roadways where the pavement is deteriorating and the linear feet of saw cut must be kept to a minimum.

Unlike induction-loops or magnetic detectors, probes and/or electronic units for magnetometer detectors are not interchangeable among different manufacturers.

Probe Characteristics. The magnetometer probe is a small cylindrical device, installed in a vertical position in a drilled hole in the pavement, usually 1-ft deep. Since the detector measures only changes in the earth's magnetic field, there is no radiated field of detection. Therefore, theoretically the magnetometer is superior to the ILD for counting. A single magnetometer probe is not recommended, however, for defining vehicle speed and occupancy in a surveillance application because of the

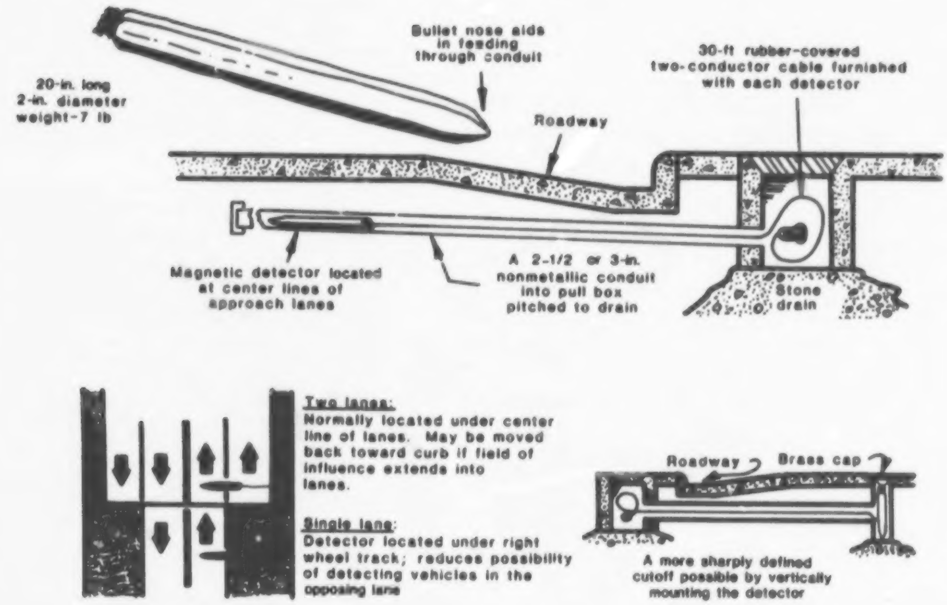

20-in. long
2-in. diameter
weight-7 lb
Bullet nose aids in feeding through conduit
30-ft rubber-covered two-conductor cable furnished with each detector
Roadway
Magnetic detector located at center lines of approach lanes
A 2-1/2 or 3-in. nonmetallic conduit into pull box pitched to drain
Stone drain
Two lanes:
Normally located under center line of lanes. May be moved back toward curb if field of influence extends into lanes.
Single lane:
Detector located under right wheel track; reduces possibility of detecting vehicles in the opposing lane
Roadway
Brass cap
A more sharply defined cutoff possible by vertically mounting the detector

Figure 5.2. Nondirectional uncompensated magnetic detector

Source: Reference (*38*)

inaccuracy of locating the exact perimeter of the vehicle with the probe. The sensitivity is also very important to the magnetometer detector system. As many as 12 probes can be connected in series to one channel of a detector unit. However, as the number of probes per channel is increased, the sensitivity at each probe is decreased (*3*).

Detectors in Early Use

In addition to the more commonly used detectors described in the preceding sections, other types of detectors include pressure, radar, and sonic detectors. Until the development of the loop and magnetometer detectors, these were considered common detectors.

Pressure Detectors. Vehicle-pressure detectors are activated by the weight of a vehicle. The weight causes closure of contact plates sealed in a rubber pressure plate which sends a signal to the controller. The contact plates normally close at 100 lb pressure or less, so that the pressure detector will operate satisfactorily for virtually all types of vehicles. A metal frame installed in the pavement provides support for the pressure plate and holds it in place.

The pressure detector was widely used for many years. However, currently it is virtually never used in normal applications, because it provides only count data, is expensive to install, requires a lane closure for extended periods during installation, and results in a dip when a roadway is resurfaced.

Radar Detectors. Radar detection operates either on a continuous wave principle or on the Doppler effect. Microwaves are beamed toward the roadway by the detector unit. The passage of a vehicle through this beam causes it to be reflected at a different frequency back to the sensing unit (antenna). The detector senses the change in frequency, which denotes the passage of a vehicle.

Basically, two types of radar units are used for vehicle detection. In one type, the sensor and detection electronics are constructed as one unit located over the roadway or in a side-fire position. In the other type, the sensor and detection electronics are separate, with the detection electronics pole-mounted at a height where the device can be easily maintained from the ground.

Radar detectors are available with two types of sensing units (antennas). The most common antenna type is adjustable for the coverage of one to three lanes. For a single lane, an optional antenna with a narrow band of detection can be used to detect traffic. The use of radar detectors requires a Federal Communications Commission (FCC) radio station license, obtainable by a state or municipality free of charge, and renewable every five years. A single FCC license will cover all the radar detectors in a city or state.

Although still manufactured and used, radar detectors are now becoming less common since they are relatively complex to maintain, are vulnerable to vandalism, and only detect motion.

Sonic Detectors. Sonic and radar detectors operate on the same principle, with both transmitting a beam of energy into an area and receiving a reflected beam from a vehicle. The sonic detector transmits pulses of ultrasonic energy through a transducer toward the roadway. The presence of a vehicle causes these beams to be reflected back to the transducer at a different frequency. The transducer then senses the change and converts it to electrical energy and relays this energy to a transceiver, which then sends an impulse to the controller to denote the presence of passage of a vehicle.

Transducers are mounted over the roadway, while transceivers are mounted in a separate cabinet or in the controller cabinet. Unlike the radar detector, which can only detect motion, sonic detectors can also be used as vehicle-presence detectors. Although sonic detectors are still available, their use is much less common than a few years ago.

Special-Purpose Detectors

This section discusses special-purpose detectors in relation to high-occupancy and emergency vehicles, environmental conditions, and pedestrians.

High-Intensity Light Detectors. A high-intensity light emitter mounted on the vehicle and a detector mounted on, or near, the traffic control signal are used in high-intensity light-detector systems. This is one type of system used for priority control for emergency and transit vehicles. Once an emergency or priority vehicle is detected, the detector relays a signal to a phase selector connected to the signal controller unit. This phase selector then checks the status of the controller unit. The selector can either extend the green interval for the emergency vehicle or terminate the green on the street or streets opposing the emergency or priority vehicle, causing a transfer of green to the direction of travel of the priority vehicle.

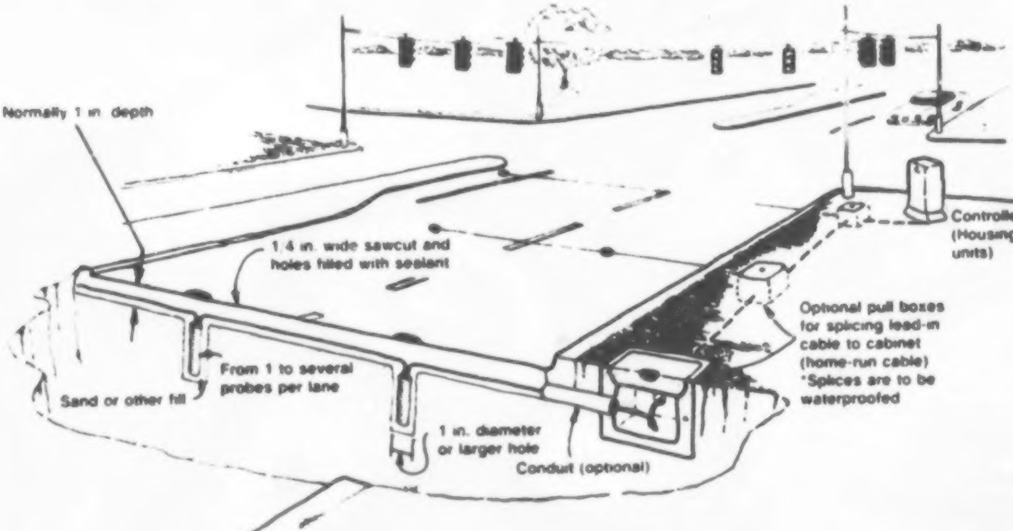

Normally 1 in. depth
1/4 in. wide sawcut and holes filled with sealant
Controller cabinet (Housing control units)
Optional pull boxes for splicing lead-in cable to cabinet (home-run cable) *Splices are to be waterproofed
From 1 to several probes per lane
Sand or other fill
1 in. diameter or larger hole
Conduit (optional)

Figure 5.3 Magnetometer detectors

Source: Reference (39)

Passive Bus Detector. An active bus detector system, consisting of a bus-mounted radio frequency transmitter, a receiving loop buried in the pavement, and a curbside receiver unit, was tested successfully in connection with the Urban Traffic Control System (UTCS) project (*42*). Because of the trouble and expense of equipping buses with transmitters, current research (*43*) focuses on the development of a passive detector that needs no transmitter on board. A bus actuation is distinguished from that of another type of vehicle by the characteristic pattern of the change in strength of the signal as the bus travels over a 6-ft by 6-ft loop buried in the roadway. The pattern is usually called the waveform or the "signature."

The loop is driven by a standard electronics unit of the type that monitors the phase of the signal induced by the vehicle. The phase is shifted according to the position and amount of metal inside the loop. A Bus Classifer Unit (BCU) observes the instantaneous phase of the induced signal, to determine the kind of vehicle, the path it takes over the loop, and the speed at which it is traveling. The waveform generated by a bus has three "humps" produced by the front axle, the fuel tank, and the rear axle/motor. The microprocessor logic of the BCU analyzes the spacings and magnitudes of the three humps to distinguish a bus waveform from that of similar vehicles such as semitractor trailers or drop-bed moving vans.

Environmental Detectors. In relation to traffic, detectors are also used to detect environmental conditions, so that traffic may be controlled or advised when adverse environmental conditions exist. Rather than actually detecting traffic, such detectors provide information and data on adverse weather conditions. Furthermore, they may activate an early warning system or traffic control system when environmental conditions are detected which may have an injurious effect on the occupants of a vehicle (such as ice, wet pavement or fog).

The principal objectives of environmental detection devices are to provide accurate surface and atomospheric data from selected locations to enable the traffic engineer to plan an efficient and safe operation. As an example, an early warning system for detecting ice conditions on critical roadway sections could save time, manpower and anti-icing material.

Pedestrian Detectors. Two types of pedestrian detection devices are mentioned below. These devices provide an input to the controller unit to allow time for pedestrian and bicyclist crossings at signalalized intersections.

Pushbutton Detectors — These are most widely used form of pedestrian demand detectors. The detector consists of a button which when pushed by the pedestrian causes a contact closure. The contact closure allows low voltage current to flow to the controller to register a demand for serving the pedestrian phase of an actuated controller unit. At the first appropriate opportunity, the WALK indication is shown for the demanded phase, followed by a flashing DONT WALK clearance display. The pushbutton is housed in an environmental enclosure to protect it from damage from weather or vandalism. The device is mechanically simple and generally reliable. All response and pedestrian timing data are contained in the intersection controller unit.

Blind and/or Deaf Pedestrian Crossings — A new type of device is being used in Bern, Switzerland, Japan, and Germany to indicate the right-of-way to blind and/or deaf pedestrians. It operates by means of a plate which vibrates when the walk signal is activated, enabling the blind to determine when it is safe to cross the street. This device has several advantages over acoustic signals because the vibrating signal is unambiguous, can be used by other handicapped pedestrians, does not disturb surrounding residents, and is not drowned out by background traffic noise (*5*).

Comparison of Vehicle Detectors

Table 5.2 compares the functional capabilities of vehicle detectors and light-emission special-purpose detectors. In most traffic signal applications, loops and magnetometers are used because of their flexibility and because they also sense vehicle presence as well as motion.

5.3 DETECTOR OPERATIONS SUMMARY

The selection of the traffic detector type to be used for any isolated intersection control or traffic control system will be dependent upon the traffic variables to be measured. As an example, since pressure detectors cannot measure presence and occupancy, the traffic engineer must determine both the types of control to be employed and the general control strategies before selecting the types of detectors and specifying their location. Vehicle detectors are designed to measure either motion or presence. Some detectors, such as the loop and magnetometer types, are capable of measuring both motion and presence.

The purpose of this section is to provide the traffic engineer with information relative to the detector-controller unit interrelationship and the techniques for the use of detectors for low-speed and high-speed approaches.

Table 5.2. Types of detectors

Detector	Measuring Capability					Method of Operation	Advantages	Disadvantages
	Count	Presence	Speed	Occupancy	Queue Length			
Loop	Yes[a] [a]Short loops (e.g., 6 ft) may be used to count. Long loops (e.g., 20 ft) do not count accurately because of the multiple occupancy on loop	Yes	Yes	Yes	Yes	Vehicle passage cuts magnetic lines of flux that are generated around the loop, thereby increasing the inductance so that a change is detected and transmitted to an amplifying circuit	1. Size and shape of detection zone can be easily set by size of loop 2. Excellent presence detector 3. Capable of measuring all traffic parameters 4. Relatively easy to install 5. Relatively inexpensive to abandon loop and reuse amplifier at new location 6. Capable of detecting small vehicles 7. Under roadway location and not subject to damage except in poor pavement	1. Cost of installation may be excessive 2. Requires closing of traffic lane or lanes for short periods of time
Magnetic, nondirectional	Yes	No	No	No	No	Vehicle passage over wire coil embedded in roadway disturbs earth's lines of flux passing through coil and induces a voltage in the coil; voltage is amplified by high-gain amplifier to operate detector relay	1. Under roadway location and not subject to damage 2. Relative ease of replacement 3. Low maintenance	1. Nondirectional 2. Difficult to set detection zone 3. Subject to false calls where located near large DC lines 4. Cannot detect presence 5. Does necessitate closing of traffic lanes for installation
Magnetic, directional (two-coil version)	Yes	No	No	No	No	Same method of operation as nondirectional magnetic detector	1. Directional 2. Not affected by DC lines in vicinity 3. Well-defined detection zone 4. Low maintenance 5. Under roadway location and not subject to damage 6. Relative ease of replacement	1. Requires closing of traffic lane for installation 2. More expensive than nondirectional magnetic detector 3. Cannot detect presence
Magnetometer	Yes	Yes	No	Yes	Yes	Similar method of operation as nondirectional and directional magnetic detectors; makes use of small cylindrical sensing head that is placed below pavement surface; measures change in earth's magnetic field caused by vehicle	1. Relatively easy to install 2. Capable of measuring count or presence 3. Reliable 4. Not affected by DC lines in vicinity 5. Under roadway location and not subject to damage 6. Relative ease of relocation	1. Requires closing of traffic lane for installation 2. More expensive than nondirectional 3. May double count some vehicles due to magnetic material distribution 4. Poorly defined detection zone
Pressure	Yes	No	No	No	No	Weight of vehicle closure of metallic contacts to complete a circuit	1. Well-defined detection zone 2. Rugged construction 3. Reliable	1. Counts axles, which yields poor count accuracy 2. Does not measure presence 3. Installation may disrupt traffic for excessive period of time

172

Table 5.2. Types of detectors (continued)

Detector	Measuring Capability: Count	Presence	Speed	Occupancy	Queue Length	Method of Operation	Advantages	Disadvantages
							4. Capable of detecting all moving vehicles, regardless of speed	4. Major resurfacing will require the use of a frame extension 5. Cannot be easily relocated
Radar	Yes	No	Yes	No	No	Passage of vehicle reflects radar microwaves (Doppler principle) back to antenna to operate detector relay	1. Immune to electromagnetic interference 2. Does not necessitate closing of traffic lanes to install	1. Relatively expensive to purchase and install, particularly if existing poles not available for use 2. Requires FCC lincense to operate 3. Requires experienced personnel for installation and maintenance 4. Does not measure presence
Sonic, pulsed	Yes	Yes	Yes	Yes	Yes	Emits bursts of energy at a rate of approximately 20 times per sec; vehicle reduces wavelength resulting in the return signal arriving when receiver is open	1. Does not necessitate closing of traffic lanes to install 2. Does not require FCC license to operate 3. Can be used at locations with unstable pavement 4. Can classify vehicle by height	1. Same as 1 for radar detector 2. Somewhat inaccurate because of conical detection zone and wide variations in vehicle configurations and heights 3. Nondirectional 4. Sensitive to environmental conditions 5. Somewhat inaccurate under congested conditions
Sonic, continuous wave	Yes	No	Yes	No	No	Operates on Doppler principle, same as radar	1. Same as 1, 2, and 3 for pulsed sonic detector plus improved accuracy for speed measurement	1. Same as for 1, 4, 5 for pulsed sonic detector 2. Cannot detect presence
Light emission photoelectric	Yes	Yes	Yes	Yes	Yes	Passage of vehicle between light emitter and photoelectric cell interrupts transmitted beam which operates a detector relay	1. Accurate for vehicle passage in a single lane 2. Most suitable for conditions of uniform light	1. Inaccurate for detection of more than one traffic lane
Infrared, interrupted beam	Yes	Yes	Yes	Yes	Yes	Same as photoelectric detector using infrared part of spectrum	Same as photoelectric	Same as photoelectric
Infrared, reflected beam	Yes	Yes	Yes	Yes	Yes	Overhead transmitter-receiver notes vehicle passage by change in reflectivity between vehicle and pavement	1. Most suitable for conditions of uniform light	1. Expensive 2. Sensitive to ambient light and color of pavement 3. Sensitive to weather conditions 4. Inaccurate because of reflective difference
High-intensity light (emergency vehicle detector)	Yes	Yes	No	No	NA	High-intensity light emitted from a device mounted on a priority vehicle is received by a light-sensitive detector indicating its presence	1. Provides a means to recognize selected vehicles	1. Expensive 2. Required equipment on vehicles

Source: Reference (*41*)

Detector-Controller Interrelationship

A vital relationship exists between the length of the timing intervals of a controller unit and the detection techniques employed. The timing of an actuated controller unit directly affects the congestion and level of safety of an intersection, while the design of the detector system likewise affects the time setting of the controller unit. By using a combination of detector placement and controller unit time settings, a traffic engineer can design a detector system for actuated intersections which improves the efficiency and safety of the intersection. The highlights of this relationship are presented in the following discussion, including detector techniques for low-speed and high-speed intersection approaches. Much of this information was derived from *Guidelines for Selecting Traffic Signal Control at Individual Intersections*, Vol. II (*6*).

Low-Speed Approaches

Approach types experiencing speeds of less than 35 mph are considered to be low-speed. The design of the detection system depends on whether the controller unit phase for that approach has been set by the traffic engineer to locking or nonlocking detection memory (sometimes termed "memory ON" or "memory OFF," respectively).

Locking Detection Memory. In a controller unit with a locking detection memory feature, a vehicle call for the green is remembered or held by the controller unit (even after the calling vehicle leaves the detection area) until the call has been satisfied by the display of the appropriate green indication. Locking detection memory is often associated with the use of small-area or point detection such as a 6-ft by 6-ft loop or magnetometer. The advantage of this approach, often called conventional control, is that the detection cost is minimized. However, this type of control is incapable of screening out false calls for the green (such as occur with a right turn on red).

Most traffic engineers desire the range of the allowable gap to be 3 to 4 sec, which means locating the detector 3 to 4 sec of travel time back from the stop line. This would be the most efficient detector position for accurately timing the end of the green, after the passage of the first vehicle of a queue or platoon.

However, the above technique is applicable only for low-speed approaches and intersections controlled by a traffic-actuated controller unit (without gap reduction). Using a practical allowable gap of 3 to 4 sec, the detector setback should not exceed 120 ft. (See Table 5.3 for a summary of this principle.)

Nonlocking Detection Memory. Preceding discussions of actuated control imply the use of motion detectors and controller unit phases set with a locking detector memory, resulting in calls being held in the controller unit after vehicles leave the detection area until a green interval is displayed for that approach. The opposite concept is setting phases for nonlocking memory with large-area presence detectors, such as a 6-ft by 70-ft loop or multiple magnetometer detectors, through loop-occupancy control (*8*). In this nonlocking mode, a waiting call is dropped (or forgotten) by the controller unit phase as soon as the vehicle leaves the detection zone. The control strategy is greatly simplified to basically respond to the presence/nonpresence of vehicles. The nonlocking

Table 5.3. Summary of detection locations and related timing for basic actuated controller units operated in locking detection memory mode

Approach Speed (Mph)	Detector Setback (Ft)	Initial Interval (Sec)		Unit Extension (Sec)		Minimum Assured Green (Sec)
15	77	8.5	+	3.5	=	12
20	100	10.5	+	3.5	=	14
25	103	10.5	+	3.5	=	14
30	120	10.5	+	3.5	=	14
35 or more	(Basic actuated controller not appropriate. Variable initial interval required)					

Note: In order to obtain a Minimum Assured Green of 12-14 sec. with a NEMA controller unit furnished under Standard TS1-1983, the Initial Interval must be set at 12-14 sec. The Local Intersection Program for a Model 170 controller unit must have the minimum green set 12-14 sec.

Source: Reference (*3*)

feature permits the controller unit to avoid the inefficiency of changing the right-of-way to an empty approach, thus reducing delay.

Loop-occupancy control was first used at intersections with a separate left-turn control, in addition to locations where a right-turn-on-red was permitted. In this application, a call placed during the yellow change interval cannot bring the green back to an empty approach. Another potential advantage exists at intersections where the left-turn vehicle is permitted to filter across during the through movement green (permissive left). To enhance this operation, some traffic engineers have used a delay detector unit which is designed to output a call to the controller unit only if a vehicle is continuously detected beyond a preset time period. During light traffic conditions, left-turn and right-turn-on-red vehicles in transit over the loop are detected, but no call is placed in the controller unit until the preselected time delay has expired, thus reducing intersection delay by omitting unnecessary phase changes.

In mild climate states where the pavement is sound and funds are ample, loop-occupancy control is also often used for through-phase detection on approaches with low-approach speeds. This technique minimizes delay by allowing the use of a snappy extension interval in the range of 0 to 1½ sec.

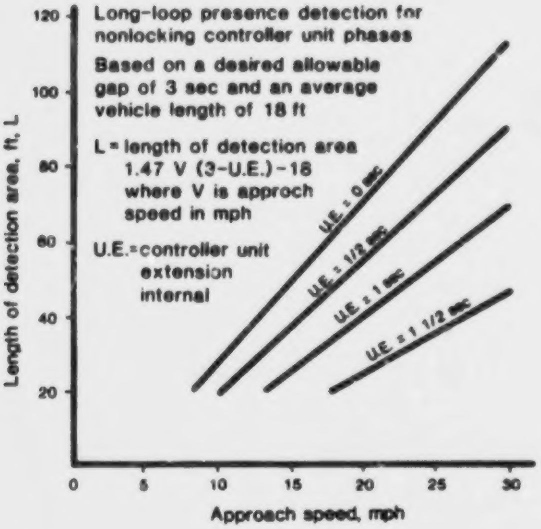


Figure 5.4. Loop length for low-speed approaches

Source: Reference (*8*)

The length of the detection area obviously depends upon the approach speed and the controller unit timing settings. For approach speeds below 30 mph, Figure 5.4 indicates a detection area length for various unit extension time settings. For approach speeds above 35 mph, a different technique is required to alleviate driver indecision in relation to the yellow change interval.

High-Speed Approaches

Approaches experiencing speeds of 35 mph or greater could, in many instances, be considered high-speed types. If the yellow change interval commences while the vehicle is in a dilemma indecision zone, it may be difficult for the driver to decide whether to stop or to proceed across the intersection. An abrupt stop may produce a rear-end collision. The decision to go through on the red may produce a right-angle accident. Table 5.4 (*9*) shows the boundaries of the dilemma zone. The data presented by Zegeer indicate that the upstream boundary of the dilemma zone, at which 90 percent of the motorists will decide to stop, is 4.5 to 5 sec from the intersection. The lower boundary, where 10 percent of the motorists will decide to stop, is 2 to 2.5 sec from the intersection. Therefore, the duration of the dilemma zone is no more than 3 sec in length, starting approximately 2 sec in advance of the stop line.

To minimize the untimely display of the yellow change interval, a traffic-actuated controller unit and appropriate detection system can be implemented. A research project examined in detail a number of advanced detector-controller unit designs for use at high-speed, isolated approaches (*10*). Table 5.5 gives a taxonomy of conventional detector-controller unit designs currently in use in the United States, with each design advanced in that it uses multiple-point detection or a density-actuated controller unit, or both. For details of the applications of these designs, see Chapters 10 and 11 of Reference (*10*). Table 5.5 demonstrates how different traffic engineers

Table 5.4. Dilemma zone boundaries

Approach Speed (Mph)	Distance from Intersection (Ft) for Probabilities of Stopping (Percent)	
	10	90
35	102	254
40	122	284
45	152	327
50	172	353
55	234	386

Source: Reference (9)

175

Table 5.5-Conventional detector-controller unit configurations for high-speed approaches

Type of System	Design	Memory	Detection Type	Controller Comments
1. Green-extension systems for semiactuated controllers	A. Two-loop B. Three-loop	Locking	Semiactuated	Compound of extended-call detectors and auxiliary logic units to hold the controller in main street phase A, until the approaching vehicle has cleared the dilemma zone. Vehicles traveling slower than design speed or termination of green by gapout may be trapped in the dilemma zone. Increasing the passage time for protection results in an undesirable allowable gap.
2. Extended-call detection systems for basic controllers	A. Extended-call (EC) design uses 70-ft loop at the stop line (normal detector output) supplemented by extended-call detector 5 sec before the stop line.	Nonlocking	Basic full-actuated	A. The stretch setting on the extended-call detectors requires compromise between snappy operation and protection for slower vehicles. The allowable gap of the EC design is typically 5 sec because of the stretch detector and long loop at the stop line. Appears limited to routes carrying less than 10,000 ADT. Design has lowest initial cost.
	B. Extended-call and delayed-call (EC-DC) design uses 25-ft loop at stop line (delay-call output) supplemented by extension detector 5 sec before stop line and a third detector between them (see Figure 5.8).			B. A stretch setting of 2.2 sec on the upstream loop will carry vehicles approaching within the speed range of 40 to 55 mph through the dilemma zone. A vehicle traveling less than 40 mph will also be protected because the yellow will appear before the vehicle has reached its dilemma zone. The 2.2-sec extension time produces and allowable gap for traffic of 3.8 sec (55 mph) and 4.4 sec (40 mph). The allowable gap is actually greater than the 1-sec difference of the EC design. The EC-DC design disables the stop line loops to give a decided superiority to EC design in real-world operation.
3. Multiple-point detection systems for basic controllers	A. Bierele modified method uses 5 detectors for 55-mph approach speeds, with farthest detector placed 349 ft from the stop bar. Uses special detector logic to determine approach speed and disable first three loops (see Figure 5.5).	Locking	Basic full-actuated	A. Bierele has modified his design for speeds greater than 40 mph. The first 3 detectors from the stop line are based on 40-mph speeds and operate on one amplifier (speed detector). Two additional detectors are placed at 1-sec intervals for 40 mph until a distance of 349 ft is reached, and tied to the second amplifier (standard detector). For speeds greater than 40 mph, the special detectors are disabled, and only the standard detectors extend the green to maintain a tolerable gap.
	B. Texas Department of Highways and Public Transportation uses primary loop detector placement designs for 45 to 55 mph (see above format)	Locking	Basic full-actuated	B. This method used AASHTO stopping sight distances (based on 1-sec perception-reaction time) for approach speeds up to 55 mph. This design is based on the assumption that a vehicle entering the loop field at the design speed will guarantee a safe stopping distance and a green if the speed is maintained or reduced by no more than 10 mph between successive loops.
	C. Winston-Salem method employs 3 sensors for 50-mph approach	Locking	Basic full-actuated	C. This method for detector placement is derived from the Bierele method, and uses stopping sight distances computed from the Traffic Engineer Handbook. The outermost point of initial detection is 240 ft for a 50-mph approach speed, which may not detect a vehicle before it reaches the dilemma time. Attempts to improve the design in that respect result in an allowable gap that is too long and frequently caused the controller to max-out.
	D. SSITE method uses 6 sensors for 50-mph approach	Nonlocking	Basic full-actuated	D. This multisensor design will adequately protect the driver from the dilemma zone, with its farthest detector set back 5 sec from the stop line. However, with its 2-sec vehicle interval, two 50-mph vehicles will cause an allowable gap of 7 sec, too long to be a design of choice.
4. Extended-call systems for density controllers	A. Single-point method composed of a presence loop at the stop line and one upstream detector	Nonlocking	Density full-actuated	A. This method provides dilemma zone protection to vehicles operating at the design speed. The suggested 2-sec vehicle interval may be insufficient for a slower vehicle to enter the usable yellow time.
	B. Multiple-point method employs a presence loop at the stop line and several upstream sensors	Nonlocking	Density full-actuated	B. The multiple-point method can be configured to afford dilemma zone protection for a variety of approach speeds and operating conditions. A queue can get into motion without gapping out and false calls can be screened out because of detection at stop line.

Source: Reference (*11*)

have combined various components of detector-controller unit hardware in their attempts to improve safety at high-speed intersections.

Studies comparing multiple-point vehicle detection with single-point detection at 10 locations by the University of Texas and the Texas Department of Highways and Public Transportation (*35*) have shown that (1) a significant reduction of accidents could be expected to occur at speeds of 45 mph and above, and (2) there was no significant reduction in delay with the use of multiple loops over the use of the single-point detector design. The results of a similar study by Parsonson/Tarnoff (in Chapter 6, Reference (*2*), however, does not agree with these conclusions.

When comparing alternatives for detector designs for high-speed approaches, the traffic engineer should weigh operational features and maintainability higher than initial cost, considering also the capability of maintenance staff and the difficulty of keeping detector loops in service. Parsonson determined that it is useful to apply the following seven criteria to judge the operational effectiveness of any proposed detector configuration for high-speed intersections (*11*):

- Does the design detect a vehicle approaching at the design speed before it reaches the dilemma zone? The design should detect the design-speed vehicle before it reaches the dilemma zone in accordance with Zegeer's data (see Table 5.4).
- What is the allowable gap imposed by this design? A short allowable gap will cause the green to terminate in a snappy, traffic-responsive manner. A long allowable gap will often prolong a green until it is terminated by the maximum setting of the controller unit. This is undesirable because a vehicle may be caught in the dilemma zone. Dilemma zone protection can be provided by using of a last car passage feature or by use of appropriate yellow change/red clearance intervals.
- On termination of the green by gap-out, will vehicles approaching at the design speed be clear of the dilemma zone? The last vehicle should be no more than 2 sec from the stop line, so that the driver has no difficulty in deciding to go through the intersection.
- On termination of the green by gap-out, will vehicles traveling slower than the design speed be clear of the dilemma zone? There is a trade-off between a snappy operation and protection afforded the slower vehicles in the traffic stream, and one can be obtained only at the expense of the other.
- Can a queue waiting at the stop line get into motion without a premature gap? Premature gap-out can occur when traffic is very heavy. Configurations using a stop line loop assure a queue can discharge without this problem.
- Can the design screen out false calls for green (as, for example, with a right-turn-on-red)? A delayed-call design of the stop line loop improves the ability to screen out false calls for the green.
- During the green interval, can a queue of left-turning vehicles hold the green as they wait to filter through gaps in oncoming traffic (on an approach without a left-turn lane and a protected left-turn phase)? Again, a stop line loop permits a queue of left-turning vehicles to hold the green as they wait for a gap in oncoming traffic.

5.4 VEHICLE DETECTOR LOCATION AND CONFIGURATION

This section will focus on alternative detector designs and the appropriate application as related to the following:

- Isolated actuated intersection control
- Urban system control
- Freeway surveillance and control

Isolated Actuated Intersection Control

Since vehicle arrivals tend to fluctuate at individual intersections, efficiency depends on responsiveness to demand that varies from minute to minute. The length of the actuated green interval is changeable and can be tailored to actual arrivals. This varying green interval (from minimum to maximum controller unit settings) is determined by the unit extensions generated by vehicles crossing the detectors. Full actuated control is the most cost-effective form of control at signalized intersections for most volume levels (*12*). Once a decision is made to install a traffic signal at an isolated intersection, full vehicle actuation should normally be used in preference to pretimed or semiactuated control.

Small-Area Detectors. Small-area detectors are those that simply detect the passage of a vehicle at a spot location (e.g., upstream of the stop line). Small-area detectors are often called short-loop, point, or passage detectors. The magnetic detector can only be used for point detection because it covers a small area. The use of short-loop detectors (less than 20 ft long) is the simplest and most commonly used type of detector application.

A common application is to space small-area loops back from the stop line to act as calling detectors for high-speed approaches, as was discussed earlier. An example of a high-speed detector design using multiple short loops is illustrated in Figure 5.5. Magnetometers also may be used to cover small areas. Some agencies use a single 6-ft-long loop to cover two or more lanes. Single point detection is relatively inexpensive, but one disadvantage is that it gives no information on the traffic that is between the downstream detector and the stop line. Figure 5.6 illustrates the contrast between small-area and large-area detection.

Large-Area Detectors. A large-area detector, usually a long loop, is designed to register the presence of a vehicle in the zone of detection as long as the detector is occupied. In this mode, the controller unit can be held in the extension interval until the vehicle detector is cleared. Thus, a very short extension interval is used. Figure 5.7 illustrates various detection designs in use today, including both small-area and large-area detection.

The controller unit may be set for either locking or nonlocking operation. Nonlocking operation avoids calling the green when a calling vehicle leaves the detection area. An alternative to nonlocking memory is to use delay-call detectors.

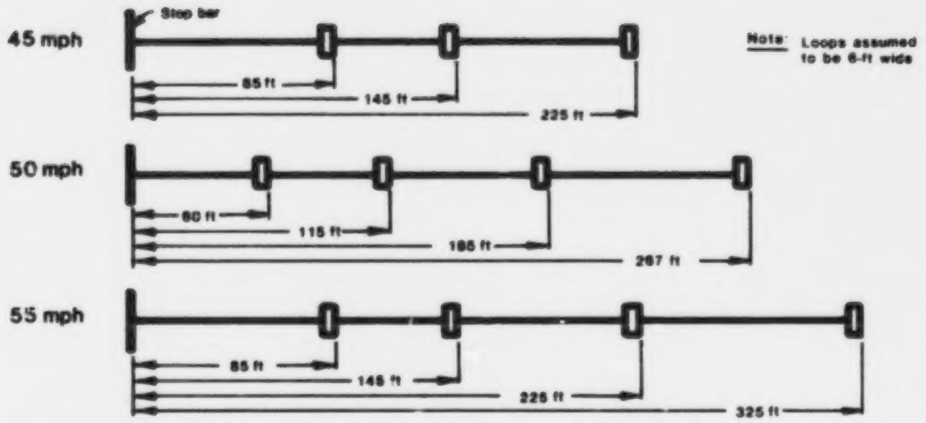
Large-area detection and nonlocking detection memory are classed as loop-occupancy control. The concept of loop occupancy is to hold the green as long as the detector is occupied and to yield the green upon clearance of the loop. This design provides a good operation when platoons are well formed, such as in low-speed approaches. However, random vehicles may cause the controller to max-out when vehicle headways are such that one vehicle can enter the detection zone just as the previous one leaves the area. Figure 5.8 shows the detector placement for the extended call and delayed call (EC-DC) design (*14*) using a combination of large-area detection at the stop line, with two small-area detectors upstream for high-speed vehicles. This detector configuration has proven very effective in real-world operation.

The disadvantages of large-area detection are that installation costs are higher, and the maintenance problems associated with long loops are greater than those for small-area detection. One way of reducing long loop problems is to use a series of 6-ft-wide loops placed parallel to the stop line and separated by approximately 10 to 12 ft. This design allows higher loop sensitivity and protection against losing a lane of detection. It is possible also to operate with one or more loops failed in this configuration, provided all lead-ins are brought back to the controller assembly separately with minor timing adjustments compensating for the failed loops. All loop lead-in cables should be color-coded or identified.

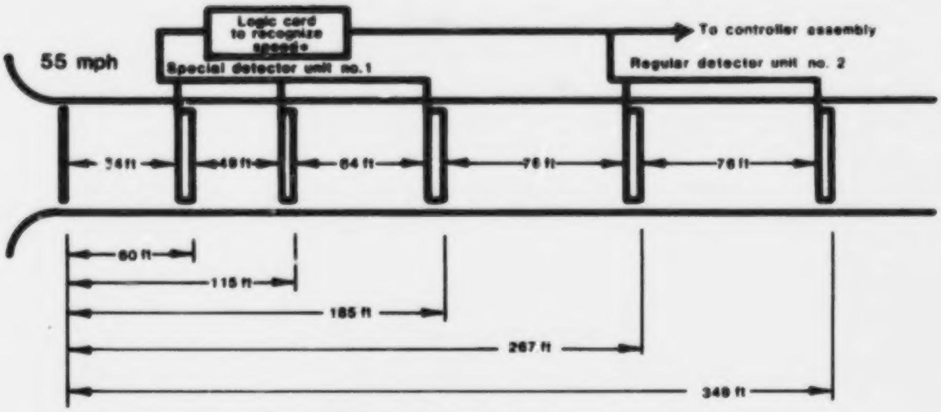
Left-Turn Lanes. The operational advantages of using large-area detection for approaches with separate left-turn control are discussed in an earlier section on nonlocking detector memory. Efficient vehicle detection in left-turn lanes can increase the capacity of an intersection by reducing lost green time. The Illinois Department of Transportation has designed a loop configuration for left-turn lanes which improves the efficiency and safety of the intersection (*15*). The design for vehicle presence actuation is based on the following premises:

- Driver reactions at the start of a green indication vary from a 3- to 4-sec startup time for the first vehicle in a queue to an average, headway of 2 to 3 sec between the following vehicles. Since these times are average to maintain the green for starting vehicles, longer times must be accounted for by adjusting the length of the loop.
- Trucks and other slow vehicles require a longer startup time often leaving a gap ahead of them that is 3 to 4 car lengths (6 to 12 sec) long. Loop length may be needed to account for these gaps where there is a relative high percentage of trucks.
- Since the length of green time is based on vehicle demand, only a short green time is needed for one to two vehicles. The length of the detection zone, however, must be sufficient for the following car either to reach the loop in time to maintain the green or decelerate to a stop.
- A vehicle extension interval of 1.5 sec permits drivers to almost complete their turning radius before the yellow change interval is displayed. Any additional extension time is lost time. A shorter vehicle extension interval was found to be disturbing to the driver when the yellow change interval appeared.
- The minimum loop length from the stop line was found to be 80 ft.
- Vehicles which are allowed to turn left on the through green (permissive), normally proceed past the stop line and wait for a gap in the opposing traffic to complete their turns. A potential problem exists when a gap does not occur and the left-turning vehicle is stranded ahead of the detection zone that ends at the stop line. The controller unit will then skip the protected left-turn phase in the next cycle, if no other vehicles are waiting to turn left. The driver may complain that the signal is malfunctioning thus resulting in an unnecessary service call. One solution is to extend the detection zone beyond the stop line.

The method of designing a minimum left-turn loop with the above requirements is shown in Figure 5.9.


Stop bar
45 mph
85 ft
145 ft
225 ft
Note: Loops assumed to be 6-ft wide
50 mph
60 ft
115 ft
185 ft
267 ft
55 mph
85 ft
145 ft
225 ft
325 ft

Controller data: Detector memory : Locking
Minimum green : 8 1/2 to 14 sec (dependent on traffic volumes, speed and number of trucks)
Extension interval : 1 to 1.2 sec


Logic card to recognize speeds*
To controller assembly
55 mph
Special detector unit no.1
Regular detector unit no. 2
54 ft
49 ft
64 ft
76 ft
76 ft
60 ft
115 ft
185 ft
267 ft
349 ft

Controller Data: Detector memory : Locking
Minimum green : 8 to 14 sec (dependent on traffic volumes, speed and number of trucks)
Extension interval : 1.0 sec

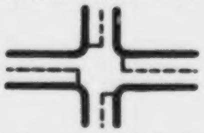
*Special detector unit output is disabled by logic card when speed of 40 mph is established

Figure 5.5. Two methods of multiple-point detection systems for approach speeds up to 55 mph

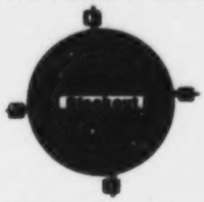
Source: Reference (*35*)

When left-turn traffic demand requires a storage length of 150 ft or more or approach speeds require a safe stopping distance, the loop layout should include advanced detection. This advanced detection, utilizing a call-extension feature on the detector, will extend the effective detection zone to accommodate heavy vehicle

1(a). The intersection



1(b). Small-area detection



1(c). Large-area detection

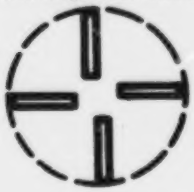


Figure 5.6. Contrast between small-area and large-area detection

Source: Reference (*12*)

or truck volumes and provide for safer operation (see Figure 5.10).

In many instances, one presence loop of 30- to 40-ft long is adequate for left-turn detection and provides a sharp operation for the left-turn phase. The designs for the left-turn lane loop varies with approach speed, presence of heavy trucks, and grade and intersection geometrics.

Detection of Small Vehicles. A large-area detector should be able to detect all licensed vehicles (including a small motorcycle) and hold its call until the display of a green to the phase. A hold time of 3 min is commonly specified. A conventional long-loop configuration (longer than 20 ft) may not detect a small-motorcycle. However, several loop configurations are available which will enhance a detector electronic unit's small-vehicle detection capability.

Some modified long loops include powerheads and angled powerheads which are small internal loops at the end of long loops with additional turns of wires. This refinement will cause a motorcycle to cut the lines of flux more efficiently, thereby increasing the inductance by as much as 25 percent (*16*). This technique is illustrated in Figure 5.11. One disadvantage of the powerhead is that the motorcycle may not stop on it unless it is clearly indicated by paint.

Another technique, termed Quadrupole (*17*), detects small vehicles by adding a longitudinal sawcut along the center of the lane. The loop wire is installed in a figure-8 pattern so that the two center wires have currents flowing in the same direction. Their fields reinforce each other and improve the capability of detecting small vehicles. The other wire's field of influence is diminished, reducing the possibility of splashover from adjacent lanes. The single-layer configuration (1-2-1) is shown in Figure 5.12. For detecting bicycles and smaller motorbikes, the loop wire is wound twice to give a double-layer design (2-4-2).

Multiple small loops, magnetic detectors, and magnetometers also have been proven to be effective in detecting small vehicles.

System Control

This section, which describes the surveillance subsystem for traffic signal systems, includes the control of arterial streets, diamond interchanges, closed networks (such as the central business district) or the control of an area consisting of networks and arterial streets. The surveillance sensors are used to provide traffic-flow information for the following system activities:

- Traffic-responsive plan changing
- Critical intersection control (CIC)
- System-aided development of timing plans for both:
  - Online algorithms in traffic control strategies such as traffic-responsive plan generation control to develop new signal timing plans when changes in traffic patterns occur
  - Offline programs such as TRANSYT, SIGOP III, PASSER II, and PASSER III to automatically format the volume input data
- Measure of effectiveness (MOE)

The selection of detector types, detector placement, and detector configuration will be dependent upon the traffic variables to be measured and the configuration of the control system. System detectors are normally located in strategic locations within the system so that traffic can be sampled. System sensors are required to provide both vehicle-count and vehicle-presence data.

System sensors usually detect traffic in a single lane and communicate only with the master computer, not with the nearby local controller units. In distributed multilevel systems, the sensor data will be passed to area controllers by the local controller unit. Some actuated

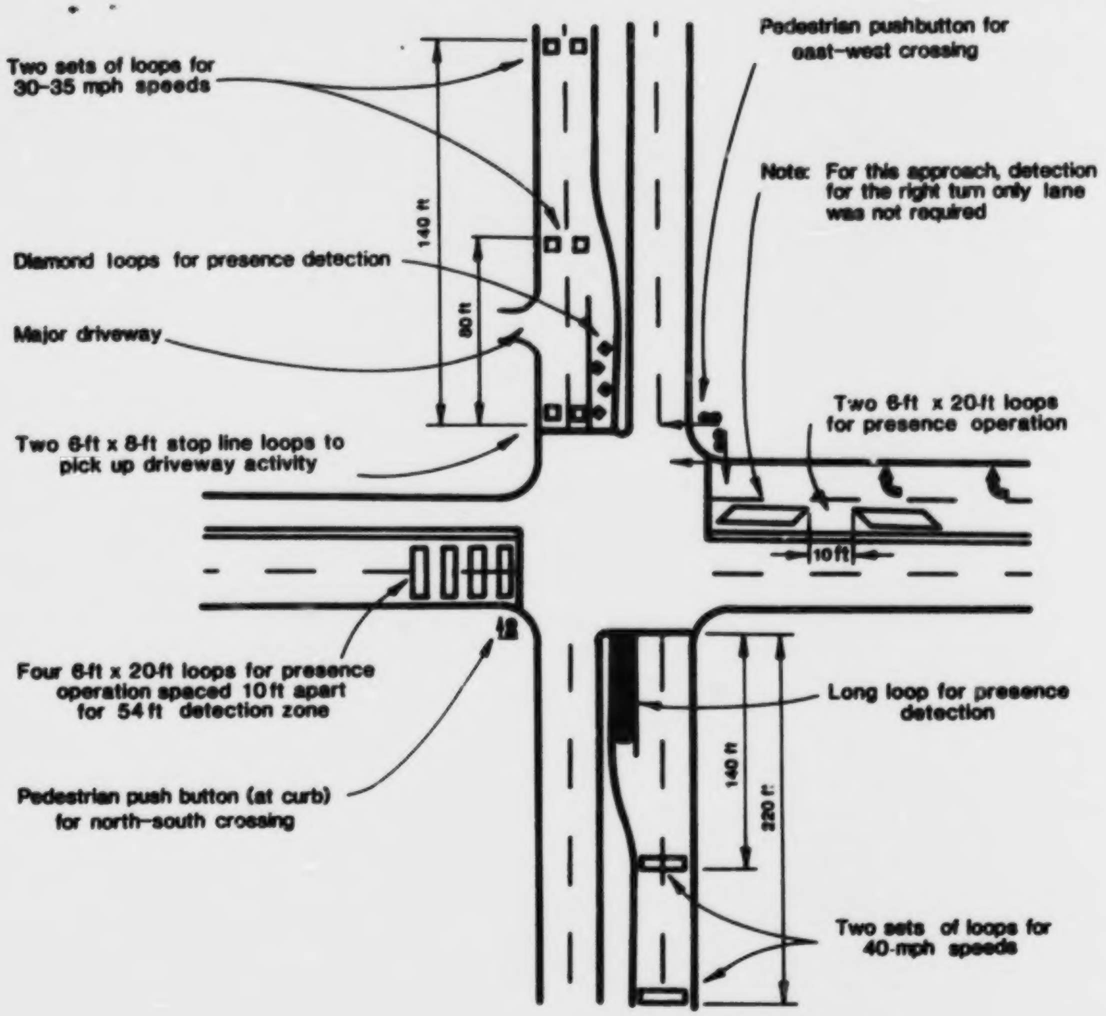

Two sets of loops for 30-35 mph speeds
Pedestrian pushbutton for east-west crossing
Note: For this approach, detection for the right turn only lane was not required
140 ft
80 ft
Diamond loops for presence detection
Major driveway
Two 6-ft x 20-ft loops for presence operation
Two 6-ft x 8-ft stop line loops to pick up driveway activity
10 ft
Four 6-ft x 20-ft loops for presence operation spaced 10 ft apart for 54 ft detection zone
Long loop for presence detection
140 ft
220 ft
Pedestrian push button (at curb) for north-south crossing
Two sets of loops for 40-mph speeds

Figure 5.7. Typical detector designs

Source: Reference (*37*)

arterial systems are designed to allow the intersections to run free in the full-actuated mode in the event traffic is very light or there is a failure of the computer or the communications. Such a design requires local detectors not only on the side-street approaches but also on all main-street approach lanes at each intersection. Since local detectors actuate only the local controller unit, their calls are not sent to the master computer.

ILD Applications for System Sensors

For data acquisition requirements as discussed, the inductive loop detector provides the broadest range for vehicle detection. Although many different types of detectors have been applied to various forms of traffic control, the ILD is most applicable to computerized traffic control. This has been demonstrated through operating

181

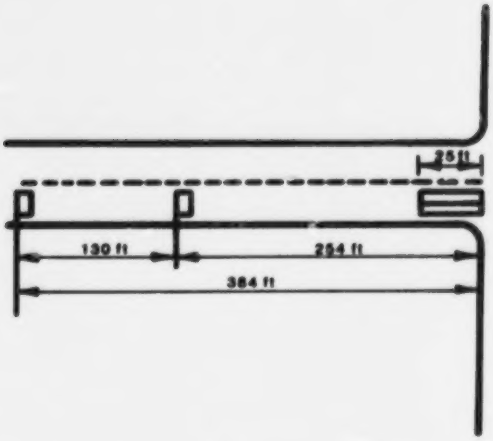


Figure 5.8. Loop location for extended call-delay call (EC-DC) design with 55-mph approach design speed

Source: Reference (*14*)

experience based on evaluation of accuracy and reliability (*18*). Since loops are capable of detecting both presence and passage, based on these two outputs and the knowledge of signal timing, a number of the following variables can be derived with varying degrees of accuracy:

- Vehicle volume
- Occupancy
- Speed
- Delay
- Stops
- Queue lengths
- Travel times

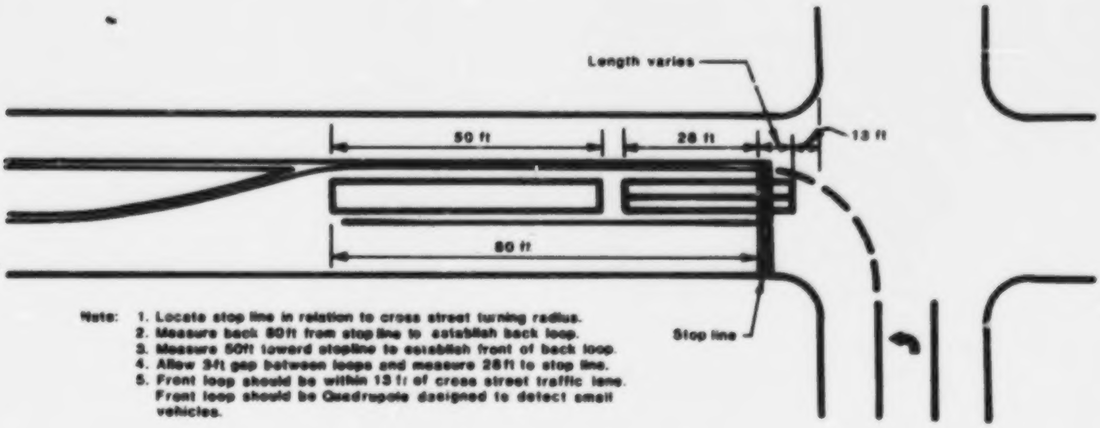
Traffic volume and occupancy are the most commonly used variables in the control of traffic. The most easily obtained quantity and the most accurate variable collected is the volume, which is defined as the number of vehicle presence pulses measured during a given time period. Occupancy is the percent of time that a detector is indicating a vehicle presence measured over a total time period. Occupancy can range from 0 to 100 percent, depending on vehicle spacing. Measuring and detecting high-occupancy levels is extremely important because, as intersections become saturated, the volume measures will level off to a constant that is proportioned to the signal green time divided by the average vehicle headways, although the occupancy will continue to increase. Observations indicate occupancies over 25 percent are a reliable indicator of the onset of congestion (*19*). The accuracy of occupancy measurement depends on the detector's area of coverage and the effective length of the vehicle (with the effective length of a vehicle depending on the pickup and dropout characteristics of the vehicle entering the detection zone). The error is introduced for vehicle presence because the detector output is sampled rather than measured continuously. Therefore, sample time (percentage occupancy) tends to be more accurate at lower speed levels than at very high speed levels. Chapter 3 describes several data-filtering and smoothing techniques and also explains how to compute the percent sampling rate. Volume and occupancy are the most important variables for use in traffic-responsive plan selection as well as for many other operating thresholds.

Speed is another useful variable for monitoring system operation. Since traffic speeds can be measured either at a point (time-mean or spot speed) or over a length of roadway (space-mean or travel speed), their data have primary value in the computation of signal timing plans. Signal-timing optimization programs such as TRANSYT-7F, SIGOP III, and PASSER II are sensitive to vehicle speeds. Errors are common in point-speed computation, however, because of the actual variation of vehicle lengths (trucks and buses). In fact, the average vehicle length may vary with the time of day and location within the network. An error of 5 to 10 percent in the computation of speeds with the above technique are common, although speed traps (the use of two detectors) at representative locations can be used to update the average effective vehicle-detector length at single-detector locations to improve the accuracy. The Surveillance, Control, and Driver Information (SCANDI) system in Detroit uses this technique to improve its average-speed computations from a single loop. Equations to determine effective vehicle-detector length and space-mean speed are found in Chapter 3.

The remaining quantities (delay, stops, travel time, and queue lengths) are used primarily for evaluation of system operation and are normally calculated from volume and occupancy. None of these variables can be measured accurately, which limits their effectiveness for control. Queue lengths and stops are extremely difficult to compute accurately unless multiple detectors are installed in each lane. However, the benefits attained from increased detectorization usually do not justify the additional expense.

Arterial Street Systems

The two basic variables used in arterial street system control are volume and occupancy. The basic strategy is to adjust the signal timing to coincide with the major



Note:
1. Locate stop line in relation to cross street turning radius.
2. Measure back 80ft from stop line to establish back loop.
3. Measure 50ft toward stopline to establish front of back loop.
4. Allow 3ft gap between loops and measure 28ft to stop line.
5. Front loop should be within 13 ft of cross street traffic lane. Front loop should be Quadrupole designed to detect small vehicles.

Figure 5.9. Detection in left-turn lanes

Source: Reference (*15*)

flow of traffic. Since, in most cases, arterial street control systems are used to establish progression along a major arterial street, a few system detectors will be strategically placed at midblock locations where traffic is free flowing. These system sensors sample inbound and outbound traffic conditions for computation of control parameters by a master supervisory unit. The master unit can vary the cycle length, offset, and cycle split on the basis of volume, occupancy, and speed obtained from the system detectors. Cross-street approaches are detectorized in much the same manner as those where isolated actuated control is used. The arterial master controller unit selects a traffic pattern based on measures of directional volume and/or occupancy as measured by the arterial street detectors. This type of operation is provided by traffic-responsive arterial master controller systems and the FACTS (*20*) minicomputer controlled system.

An example utilizing an arterial master controller unit is the distributed multilevel system in Eureka, California, which consists of three levels of Model 170 controller units. The Level 1 supervisor program (L1S) can select one of nine timing plans or free operation for the local intersections in its control. The L1S traffic-responsive

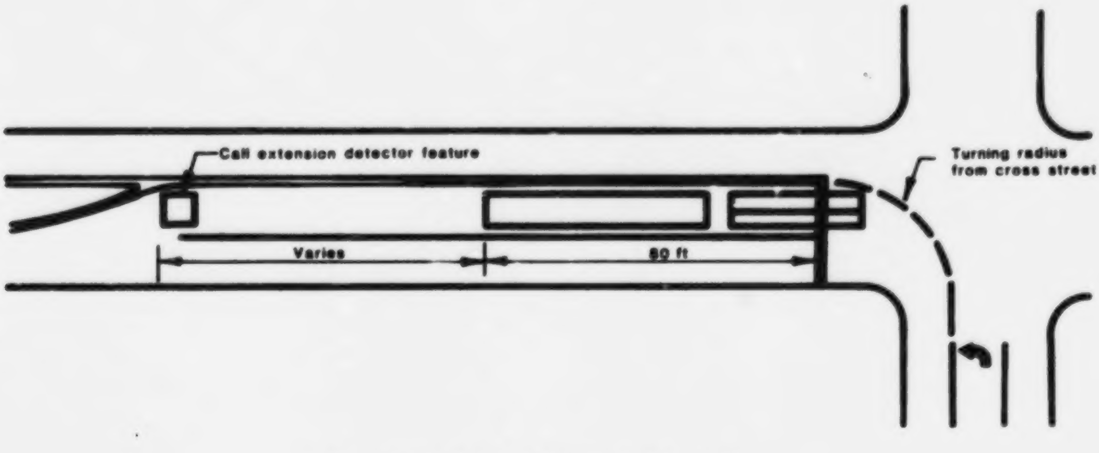

Call extension detector feature
Turning radius from cross street
Varies
80 ft

Figure 5.10. Extended detection in left-turn lanes

Source: Reference (*15*)

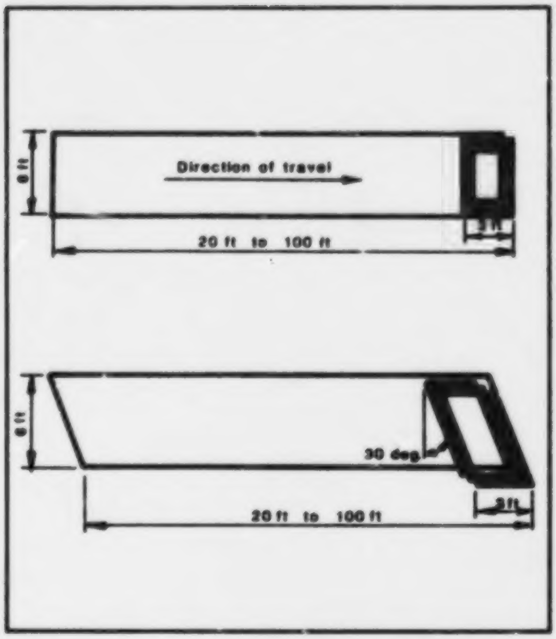


Figure 5.11. Powerhead configurations

Source: Reference (*8*)

plan is selected by averaging selected inbound and outbound detector values throughout the arterial and comparing this value with operator settable thresholds. Chapter 7 discusses other types of system masters. An example of an arterial street system that does not utilize an arterial master controller unit is the DARTS System (*20*) used in Texas, consisting of a series of signals using NEMA controller units, each with an external coordination unit and vehicle detectors placed on the arterial approaches to detect high-speed vehicles. When a "static" platoon is detected and released at a given signal, the coordination unit starts a timer to inhibit detector inputs to controller units at downstream intersections to hold the green for the arterial phase. Platoon coordination is achieved on an intersection-to-intersection basis by the use of the standard intersection detectors. A similar design is incorporated into at least one commercially available traffic-responsive microcomputer type arterial master controller system as an option to traffic pattern selection under designated traffic conditions.

Network Control Systems

The surveillance requirements of areawide traffic control are dependent upon the type of control to be implemented. Time-of-day control does not require any detectorization because it is basically a time-clock operation. However, first-generation traffic-responsive control requires detectorization that is capable of timely identification of traffic trends within a system. This detectorization must be capable, for example, of providing an indication of a peak period for the beginning of heavy traffic. Therefore, the detectors must be placed on heavily traveled links with traffic patterns representative of the significant flows contained within a controlled section.

For traffic-responsive plan (TRSP) generation-type control systems (*36*), detectors are nominally required on all approaches. However, when using versions of optimization programs, several criteria can help reduce the number of detectors while maintaining adequate accuracy in preparing online signal-timing plans. This automation process relies on the use of detector data automatically collected by the traffic control system.

The location of detectors in a traffic control system is a 3-step process in which detectorization links are selected, followed by lateral and longitudinal detector placement selection. The remaining part of this section describes this process.

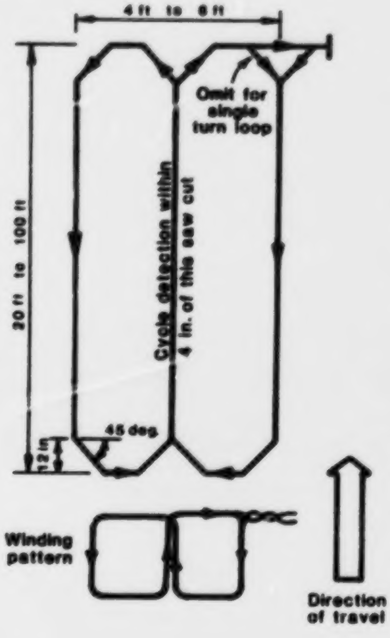


Figure 5.12. Quadrupole-loop configuration (1-2-1) design

Source: Reference (*8*)

Selection of Links. The selection of links is an important step since the surveillance system cost is directly proportional to the number of detectorized links. A link is defined as a section of roadway between two signalized intersections carrying a single direction of traffic flow, and its selection is based on several factors, including the following:

- Type of control strategy to be implemented
- Intersections requiring critical intersection control (CIC)
- Major traffic flow patterns within the day
- Distance between adjacent intersections
- Number of major generators between intersections
- Special-event timing
- Evaluation of system operation
- Automation of traffic counts

First-Generation Control — The number of detectorized locations is first determined by the type of control to be implemented. First-generation control usually requires an average range of 0.5 to 1.5 detectors per intersection. Link selection for first-generation control is begun by considering which intersections are candidates for Critical Intersection Control (CIC). The candidate intersections are those that have varying traffic demand and can take advantage of variable split but which operate in an unsaturated condition. When an intersection is being detectorized to operate under CIC, all approaches served by phases with variable green times also must be detectorized. "Locating Detectors for Advanced Traffic Control Strategies," *Handbook* (*21*), details a step-by-step procedure for determining candidates for CIC.

With traffic experience of the control area determined and the collection of traffic volumes secured, it is possible to define major flow patterns for various times of the day within the network. Once the major circulation patterns have been defined, only the links having the most pronounced and earliest traffic peaking characteristics should be chosen for further study.

Figure 5.13 indicates that various volume plots have pronounced peaking, and many of these may be detectorized for traffic-responsive operation. In the same figure, links A, B, C, and D have been determined to carry the major traffic flows in the network. Since the traffic counts made throughout the day show that link A provides the earliest indication of the beginning of the a.m. peak traffic, this link should be a primary candidate for detectorization. Likewise, since links B and C provide equally distinct indications of the p.m. peak condition, one of these should also be considered for detectorization. Since link C indicates a distinct difference in operation between the a.m. and p.m. periods, this link is preferred. As a result of this analysis, links A and C have been selected. It should also be noted that link D carries too low a traffic volume to provide a reliable indication of changes in demand. Links carrying low traffic volumes should be avoided because their normal cycle-to-cycle fluctuations in demand can cause misleading indications. This technique is applicable to a wide variety of network types. For example, the same procedure can be used to determine the detectorization requirements of an arterial. Large networks can be divided into sections in which the representative-flow technique is applied.

The need for measuring general traffic trends will probably be satisfied by the CIC and areawide surveillance detectorization. If such equipment has not been installed because of a planned time-of-day operation, the detectorization for measuring general trends should be located instead on major collectors or distributors to the network in order to obtain system trends with a minimum amount of instrumentation. Another group of candidates for this type of detectorization are entrances and exits of parking lots or special-event facilities that are large enough to have a significant effect on local traffic conditions.

TRSP-Plan Generation Control — When designing for TRSP plan generation operation or offline signal-timing computation, it is nominally required that all approaches to signalized intersections be detectorized. "Specifications for Los Angeles ATSAC System" (*22*), however, are developed to provide criteria which can be used to reduce the number of detector locations without significantly affecting the level of accuracy of the online timing-plan calculations. The surveillance system accuracy will depend not only upon the number of detectors installed, but also on their locations on the streets within the control area. The criteria established by JHK & Associates (*22*), which are based largely on the results presented in "Locating Detectors for Advanced Traffic Control Strategies," *Technical Report* (*23*), are discussed below:

- Main street volume criteria — Tests were conducted by Henry, Smith, and Bruggeman in order "to determine how good a predictor the count at the upstream detector is of the traffic on the downstream link" (*23*). The most significant conclusion that Henry makes in this report is that the coefficient of variation between detectors tended to *improve* as the link volumes increased. This is particularly important because the effectiveness of the timing plans developed using TRSP plan-generation control will be a function of the accuracy within which the surveillance

185

system reflects traffic demand at the intersection approaches. It was also concluded that a coefficient of variation of less than 0.2 in the estimate of hourly traffic volume on an adjacent link will result if the traffic volume is greater than 400 vph on the critical through lane. Therefore, links for the Los Angeles ATSAC System are not candidates for detectorization if the following threshold volumes exist:

- ◻ A single downstream link not instrumented volume greater than 400 vph per lane
- ◻ Two downstream links not instrumented volume greater than 450 vph per lane
- ◻ Three downstream links not instrumented volume greater than 500 vph per lane

- Turning-movement criterion — The number of links instrumented can be further reduced where the side streets have a low percentage of turning volumes. As a general rule, a link will not have to be instrumented if no single turning movement (from the side street onto the link or from the link onto the side street) exceeds 5 percent. This rule should not be applied to a sequence of links because the errors introduced by the turning movements tend to accumulate.
- Side-street volume criterion — Traffic volumes on minor side streets will have little impact on signal-timing calculations since the side-street green times at these locations will be controlled by the minimum green times. In networks, low side-street volumes will have only a minor influence on the offset calculations because the delays experienced by light volumes will not significantly affect the performance of the overall network. For these reasons, an additional threshold can be established that eliminates a link as a candidate for detectorization when the side-street volume is lower than the specified threshold.

The location of detectors to evaluate system operation is dependent upon the degree of accuracy required by the evaluation. If a general evaluation of changes in system operations is desired, the detector placement for TRSP operation described for first-generation control would be adequate. If a more detailed evaluation is required such as identifying changes in speeds and delays of less than 5 percent, it will be necessary to increase the number of detectors within the system. When the cost of this increased detectorization is evaluated, it may be more cost-effective to conduct traffic engineering studies such as floating car studies, rather than to increase the number of system detectors.

Some computer surveillance systems are used to collect the data normally associated with cordon counts around a CBD. This type of data requires the installation of vehicle detectors in every lane rather than restricting it to single-lane detectorization unless gross expansion factors are used.

Lateral Detector Placement. The lateral positioning of detectors refers to the lane or lanes in which they are to be installed. In general, detectors must be capable of measuring the highest lane volume at the intersection approach. The work by Henry, Smith, and Bruggeman (*23*) indicates, that at the midblock location, the lane designated as the critical lane did not change over the entire daytime period for approximately 65 percent of the cases. Because the lane volumes are more evenly distributed at the intersection, it is possible that the critical-lane designation may change more frequently in this area. Verification of this fact will require field measurement. The time spent making these measurements will be more than offset by the savings in system acquisition costs. Therefore, it is recommended that the critical-lane detectorization approach be used where possible, and that this approach should be based on a field-measurement program conducted during the system-design phase. The recommended steps to identify the critical lane on all links where it is not directly obvious from observation is taken from Kay (*21*):

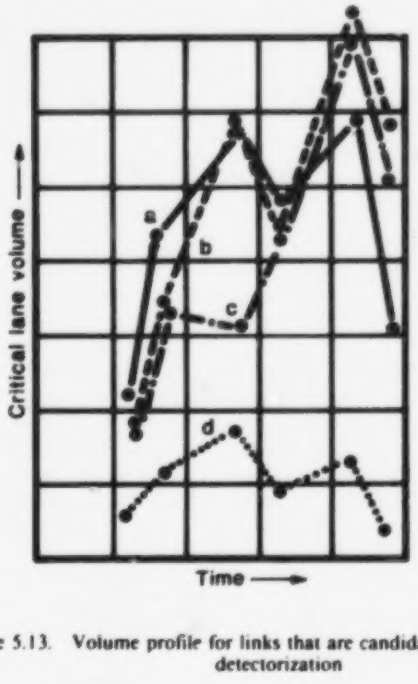


Figure 5.13. Volume profile for links that are candidates for detectorization

Source: Reference (*19*)

146

- Identify the intersection approach requiring detectorization
- Conduct measurements for 20 signal cycles during the a.m., p.m., and midday periods at each intersection approach
- Collect the data by positioning manual observers within 35 ft of the stop lines
- Record data (by one observer) and note the signal cycle and inform the other observer(s) of the start of the green interval for the approach being evaluated
- Count (by other observers) the number of vehicles crossing a predefined point in the roadway in each lane during each single cycle
- Analyze the data by comparing the volumes measured for the approach lanes

  For each time period, the lane with the maximum total volume over the measurement period should be identified; if the same lane is the maximum for each measurement period, and if its volume is greater than that of all other lanes for at least 16 of the 20 cycles in each period, then this lane is identified as the *critical lane;* otherwise, multiple-lane detectorization will be necessary.
- If the critical lane fluctuates with the time of day, multiple lanes should be detectorized. Means of incorporating time-of-day factors in the control software will be necessary so that the proper detector is measuring the current critical lane volumes.

In many cases, simple observation of an intersection will be adequate to establish the critical lane. It will only be necessary to conduct these more detailed measurements in areas where a short-term observation of the intersection operation will not permit critical lane selection.

Longitudinal Detector Position. Of the two different guidelines for the longitudinal placement of detector on a link, the first relates to first-generation control, while the second is related to TRSP plan generation control.

First-Generation Control — Function requires an accurate occupancy measurement to support the software. Kay (*21*) concluded that detectors should not be close to either the upstream or downstream intersections. Since the lane discipline in the vicinity of the intersection is very poor, lane-changing maneuvers near the intersections (especially upstream of the intersection) can produce large errors in both volume and occupancy.

A distance of approximately 230 ft from the stop line of the upstream intersection is recommended. From the downstream intersection, the detector should be upstream from the point beyond which standing queues of vehicles do not typically extend. Although this distance is a function of the cycle length, split, and offset, it is recommended that the following be used:

- Urban grid areas: 200-250 ft
- Suburban arterials: 300-350 ft

When both criteria cannot be met, the criteria based on typical queue size is considered the more critical (*21*).

One additional longitudinal-detector placement issue concerns detector location related to traffic sinks and sources. Detector-placement research indicates that a sink/source has only a minimal effect on the traffic measured in the critical lane when the facility is operated as a sink, such as a parking garage during the morning peak. This situation results because vehicle turns into the sink are executed from the curb lane, which is not usually the critical lane. Only during the evening peak hour, when the facility is functioning as a source, were there measurable effects on the critical lane.

An evaluation of the paths of vehicles entering the lane from a source, indicates that most vehicles wait for a sufficient gap to enter the specific lane within the link. It is suggested that a critical lane detector be located at least 50 ft downstream from the source, provided that the downstream intersection criteria described earlier is met. In general, unless the source contributes more than 40 vph to the critical lane, the effects of a source on the link demand are not significant.

TRSP-Plan Generation Control — Longitudinal detector placement for TRSP plan generation control is different from TRSP plan selection (pattern matching) used in first-generation control, since the signal timing plans are essentially developed, or generated, in real time. A primary role of the detector data is for the collection of volume information as an input to the signal-timing optimization program.

In the selection of the detector location consideration should be given to the accuracy with which the detector can measure the heaviest turning movement or lane volume (critical-lane volume) existing at the intersection. While midblock volume measurements may be an accurate indicator of relative demand and changes in demand, a significant change in the lane distribution will reduce the value of midblock volume measurements as data for intersection split calculations. There is a poor volume correlation between midblock detectors (located more than 200 ft from the stop line) and detectors located near the stop line. According to Henry, the "poor agreement is caused by lane changing within 200 ft of the intersection. Particularly at relatively low volumes, vehicles were observed to favor the middle lanes to avoid midblock marginal friction then fan out into all lanes at the intersection" (*23*). Also, heavy turning movements cause a change in the lane distribution which affects the offset and splits of the downstream intersections. In Los Angeles ATSAC, where TRSP plan generation is a part of the control strategy, the volume detectors are located within 35 ft of the stop line.

One implication of placing detectors near the stop line is that they will not be capable of providing accurate occupancy and speed measurements required to support TRSP plan first-generation control functions. Large errors in the measurements of these variables are caused by stopping vehicles (queued from the stop line) over the detectors, thus indicating high occupancy and low speed. While speed is important, it can be derived from relatively few sampling detectors for a given section of roadway with homogenous traffic conditions. In addition, past experience has shown that the existing speed should not be used directly by most optimization programs, but should be manually adjusted upward to represent the desired speed for progression. Therefore, a detailed detectorization plan is required to provide the desired accuracy for the particular TRSP plan generation control operation.

General Guidelines for Spotting Detectors. The information presented in previous sections will help in selecting links to be detectorized, the lanes in which the detector should be placed, and the approximate longitudinal location with respect to the upstream and downstream intersections. After these analytical procedures and the detectorization plan have been completed, the system user should literally walk through each noted link to select final detector locations. This field check should also consider access to the intersection controller cabinet, special driveway problems, pavement conditions, and manhole locations.

In summary, the final decision concerning the location of detectors for advanced traffic control strategies is a blend of analytical procedures and application of engineering judgment. It must be recognized that not all links can be instrumented to yield input measures within the accuracy required of the algorithms. Short links, as well as links with extremely poor lane discipline, are typical of those that are not amenable to accurate instrumentation.

Freeway Surveillance and Control

Detectors are one of the most important elements of freeway surveillance and control. In existing freeway systems, detectors are used for ramp metering, mainline detection, and incident detection. Two types of detectors have generally been used for freeway control and surveillance applications:

- Inductive loop detectors (ILD)
- Magnetometers

While other types of detectors have been used for specific applications, these two are the ones primarily used for freeway surveillance and control. Of these, the magnetometer has only been used on a few major freeway systems such as in Baltimore and Dallas. On the other hand, the majority of traffic engineers in the United States are convinced that the ILD detector has proved to be the best available for use in freeway surveillance and control systems (*24*). Perhaps the major reasons for the ILD's popularity can be summarized as follows:

- Best type of detector for sensing presence and queue length
- Extremely flexibility, with a large variation in loop size possible for different applications
- Usefulness for obtaining measurements of speed, either in pairs separated by a short known distance or with of an average vehicle length applied to the measured time of occupancy
- Interchangeability of detector units among manufacturers

Detectors are needed for freeway surveillance and control to detect two types of congestion associated with freeways — recurring and nonrecurring. Recurring congestion refers to freeway congestion where both the location and time of occurrence can be predicted with a high degree of accuracy. Nonrecurring congestion is that caused by random, temporary incidents such as stalled vehicles, spilled loads, or other accidents or nonpredictive events.

Recurring congestion results when freeway demand exceeds freeway capacity. One solution for recurring freeway problems is to decrease peak period freeway demand by managing the vehicular activity through the following techniques:

- Entrance ramp control
- Mainline metering
- Freeway-to-freeway connection metering
- Corridor control

Nonrecurring problems creating congestion are more difficult to manage because their locations and times are not predictable. The approach to minimizing the effects of nonrecurring congestion is one of detecting the incident and removing its effect on freeway capacity as soon as possible. Major surveillance techniques that have been used to detect incidents include the following:

- Electronic surveillance
- Closed-circuit television
- Aerial surveillance
- Emergency callboxes
- Emergency telephones
- Motorist aid systems
- Citizen band (CB) radio
- Police surveillance patrols

All of the above techniques to improve freeway management have been discussed in detail in Chapter 4. The following section describes the various control techniques which use detectors to manage freeway operational problems such as ramp metering, mainline detection, and incident detection.

Ramp Metering. Freeway surveillance and control systems have been placed into operation in a number of U.S. cities, including Atlanta, Chicago, Dallas, Detroit, Houston, Los Angeles, New York, and Seattle. These freeway control systems, as well as others that are in the planning or construction phase, can be divided into three basic traffic control groups:

- On the mainline
- At exit ramps
- At entrance ramps

Freeway traffic control at the entrance ramp is the most widely used type. Entrance ramp metering may operate in either a pretimed or traffic-responsive mode. Pretimed metering usually does not require the use of ramp detectors; however, one version of this type of metering makes use of a loop detector located adjacent to the stop line at the ramp signal. This detector, referred to as a checkin (or demand) detector, will cause the ramp signal to turn green only when a vehicle is waiting (*24*). This type of metering is illustrated in Figure 4.7.

Traffic-responsive ramp metering consists of monitoring traffic on the freeway, the ramp, and the approaches to the ramp. Detectors are monitored either by the local ramp controller or a control computer, and metering rates are adjusted by control programs based on inputs from the ramp and freeway mainline detectors. Everall outlines a possible configuration of ramp and freeway detectors which is illustrated in Figure 5.14 (*24*). The number and type of detectors (volume, occupancy, and speed detectors) depends on the overall control and surveillance strategies being used. Only some of the detectors described below and illustrated in Figure 5.14 are used in any one system.

In Figure 5.14, items D_{1V} through D_{6V} are volume detectors in the freeway main lanes. These detectors may be simple motion detectors, or they can more effectively be used with other detectors to determine average speed and occupancy. The freeway mainlane occupancy detectors are D_{20} and D_{50}, with D_A and D_B the shoulder-lane freeway mainline presence detectors, set approximately 20 ft apart, for measuring vehicle spacings and speeds. These detectors provide data used to project gaps in the outside lane. The ramp presence detectors are D_M, D_Q, and D_1. Usually a motion detector, D_{CO}, notes passage of a vehicle through the ramp signal. Upstream of the ramp signal, D_Q and D_1, measure the respectively presence of a vehicle waiting to enter the ramp as well as the presence of a vehicle waiting at the signal. A merge detector, D_M, operating in the presence mode, is located downstream of the ramp signal to detect a vehicle stopped at the end of the ramp waiting to merge onto the freeway.

A composite of detector designs for various freeway ramp control and surveillance strategies is shown in Figure 5.14. The exact location and number of detectors will be dependent upon the control strategies used. A description of the various control strategies may be found in Chapter 4, along with a discussion of detector location in support of the gap-acceptance merge-control system. Also, in NCHRP Report 232 (*25*) are guidelines that provide the traffic engineer with information and the methodology to guide and assist in determining the feasibility and type of entrance ramp control on freeways. The following comments are extracted from Everall's report (*24*) regarding freeway-ramp-detector configuration and location:

- Checkin (demand) detector, D_1 — Must sense presence of vehicles at head to queue to actuate ramp signal. On single-entry ramps, the width of the detector should be a function of ramp width, or approximately 6 ft. The detector length should be sufficient to detect a vehicle that does not stop exactly at the stop line, but should not be long enough to detect two waiting vehicles. Present thinking suggests a 15-ft-long detector located no further than 5 ft upstream of the ramp signal.
- Checkout (passage) detector, D_{CO} — Normally senses the passage of a vehicle (motion detector). A standard loop 6-by-6-ft loop is used and located 6 to 8 ft downstream of the ramp signal. If this detector is also used as a vehicle-classification detector, it should be located further downstream, 50 to 100 ft from the

ramp signal. This is a point at which vehicles are more likely to be moving and will be unlikely to stop over the detector.

- Merge detector, D_M — Size and location will be dependent upon ramp geometrics. The detector should be able to pick up any stopped vehicles in the merge area; however, vehicles traveling in the freeway shoulder lane should not be detected by the merge detector. If possible, a trapezoid-shaped detector should be used.
- Queue detector, D_Q — Should be located as far upstream on the ramp as possible without detecting the frontage road traffic which desires to bypass the ramp. The length of the queue detector should be in the range of 12 to 20 ft.
- Volume and occupancy detectors, D_{1V}-D_{6V}, D_{20}, D_{50} — Location and number will be dependent upon the overall surveillance and control strategies being used. Normally, a 6-by-6-ft detector located in the freeway lane being monitored will be used.
- Approach detectors, D_A and D_B — Should be located at a point on the freeway shoulder-lane where the speed is representative of the speed that will occur at the merge area. The 6-by-6-ft detectors should be located approximately 20 ft apart. It is necessary for D_B to be located upstream of the ramp nose at a distance equal to, or greater than, a distance d defined as follows (*24*):

$$d = S_{max} (TT_R + G_{max}) \qquad (5.1)$$

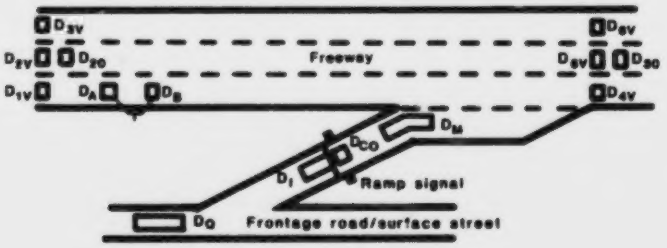
Where:

S_{max} = Highest speed in the outside lane during time of control

TT_R = Ramp travel time from ramp signal to the merge area

G_{max} = Maximum gap setting in the controller

Mainline Detection. As described in Chapter 4, mainline control is concerned with traffic regulation, warning, and guidance on the freeway itself. In most cases of present usage, mainline detection is used to provide input for control strategies used in traffic-responsive ramp metering. Recent installations, however, have expanded mainline-detection systems to accommodate comprehensive freeway management concepts such as incident detection and driver-information systems. Mainline detectors to support freeway incident detection and control are described in a following portion of this chapter. The functions of mainline detectors, shown in



D_{1V}, D_{2V}, D_{3V}, D_{4V}, D_{5V}, D_{6V} = Volume detectors in the freeway mainline

D_{20}, D_{30} = Occupancy detectors

D_M = Presence detector in the merging area

D_Q = Queue detector

D_I = Checkin detector

D_{CO} = Checkout detector

D_A, D_B = Presence detector used to measure speed and vehicle spacings

Note: The detectors shown above are a composite of possible loop designs and are not installed in any one freeway system. The number and type of detectors (occupancy, volume, speed detectors) used in a specific system operation will depend on overall control and surveillance strategies applied by an agency.

Figure 5.14. Possible location of detectors at freeway entrance ramp

Source: Reference (*24*)

190

Figure 5.14, which also support traffic-responsive ramp metering are described in the following listing:

- Demand/capacity control — Detectors D_{1V}-D_{2V}-D_{3V} measure the demand rate upstream of the ramp. Detectors D_{4V}-D_{5V}-D_{6V} measure the downstream flow. Upstream demand and downstream flow are then compared to determine the desired ramp metering rate.
- Occupancy control — Detector D_{20} measures upstream occupancy. Metering rates are based on calibrated data relating occupancy to other traffic parameters such as volume and speed. These data allow the controller to select an appropriate metering rate based on the measured occupancy.
- Shoulder-lane control — Detector D_{1V} measures the volume in the shoulder lane. This measurement may be compared with either the known capacity of the shoulder lane downstream or the downstream shoulder-lane volumes measured by detector D_{4V} to determine the metering rate.
- Gap-acceptance merge control — Detectors D_A and D_B detect and measure gaps in the shoulder lane. As soon as an acceptable gap is detected in the shoulder lane (as determined from the control parameter established by traffic conditions on the freeway), a ramp vehicle is released by the ramp signal to meet this gap in the merge area.
- Gap-acceptance demand-capacity combination — The ramp signal is operated at a metering rate which is determined by demand-capacity, but which also releases vehicles to meet available acceptance gaps.

Principles for placement of a loop or magnetometer probe relative to the roadway differ with the intended application. However, there are some specific principles that should be addressed when these sensors are placed on the mainline of the freeway. If both volume and speed information is to be extracted from the presence indication of loops or probes installed in the mainline, limits are placed on the effective length of the sensor. The effective length is the distance in the direction of traffic flow between the point where an average vehicle is first detected and the point where it is last detected after having passed over the sensor.

An obvious limit is that the length should not be greater than 17 ft because a greater length will not allow detection of consecutive vehicles whose intervehicle gap is as small as a one-vehicle length. A very short effective length will require a high detector sampling rate which, in turn, increases the cost of the communications hardware required and places an additional computational burden on the central computer (*26*). A 3-ft effective length, corresponding to a single magnetometer probe, would be an absolute minimum. The effective length of a loop is slightly more than the actual length of the loop. Figure 5.15 illustrates a paired-loop configuration for accurate speed measurements.

Blikken, an operations engineer with the Michigan Department of Transportation (MDOT), investigated several different loop configurations when designing and installing the SCANDI project in Detroit (*27*). The SCANDI experience found that it is best to install loops so that they are diagonally disposed to the direction of travel, as shown in Figure 5.15. Either diagonal or diamond-shaped placement is best since the detection zone

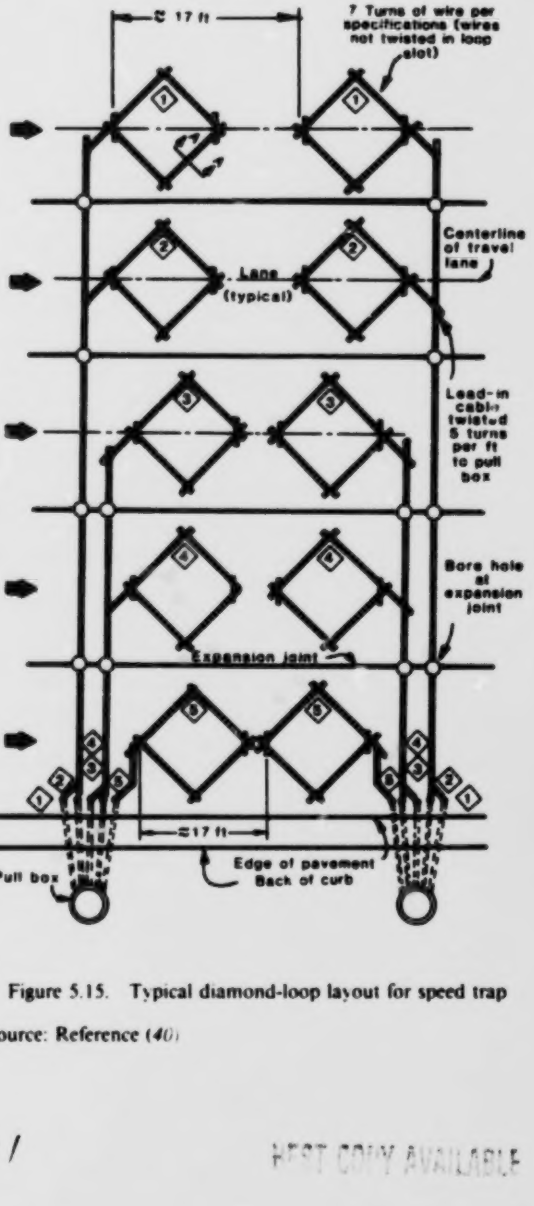

≈ 17 ft
7 Turns of wire per specifications (wires not twisted in loop slot)
1
2
3
4
5
Centerline of travel lane
Lane (typical)
Lead-in cable twisted 5 turns per ft to pull box
Bore hole at expansion joint
Expansion joint
≈17 ft
Edge of pavement
Back of curb
Pull box

Figure 5.15. Typical diamond-loop layout for speed trap

Source: Reference (*40*)

191

of a square or rectangular loop "bows out" along the sides, sometimes by as much as 3 or 4 ft, but only a few inches from the corners. Consequently, the effective length of the loop is virtually identical with the diamond-shaped loop giving better measurement accuracy and consistency. Furthermore, the electromagnetic field is more intense at the corners, which results in a more sharply defined inductance change when the vehicle enters or leaves the loop. Additional benefits include better sensitivity to motorcycles and a reduction in adjacent lane interference (splashover). Blikken also adjusted the diamond loops by varying the angle of the sides so that all loops had the same width of sensing zone; that is, to cover only one lane at a given detector sensitivity. Blikken has received a patent on the adjustment process (U.S. Patent No. 4,239,415).

One of the requirements under the SCANDI program was that all vehicles were to be detected as a single entity, including high-bed trucks, semitrailers, and tanker configurations. Initially operations began by testing a 3-turn, 6-by-6-ft loop, and found that it would not adequately detect high-bed vehicles. In their tests, personnel found that apparently the sensitivity had to be increased by four in order to detect semitrailer rigs. MDOT solved the problem by increasing the number of turns in the loop to 7 (*27*). To save installation time (freeway closure), the 7-turn loops were previously wound in the shop. This step has saved approximately 10 min per loop installation, in which every minute is critical during mainlane closure.

Incident Detection. In incident detection, freeway conditions are examined for nonrecurring problems, such as accidents and vehicles stalled on the freeway. Incident detection requires the use of a large number of detectors. However, if occupancy or some other sophisticated type of ramp control is being used, many of these ramp-control detectors could also serve incident-detection needs. Incident-detection systems are operating in Chicago, Los Angeles, Detroit, Seattle, Tampa, and the San Francisco Oakland Bay Bridge.

The basic principle involved in most vehicular detector-based surveillance systems is that changes in the percentage of time that a vehicle is present between adjacent detectors (lane occupancy) are used to sense congestion and indicate that an incident has occurred. A computer calculates the difference in occupancy between adjacent detector stations. At the end of each sampling period and when the occupancy and that of the preceding sample for the downstream detector exceeds a certain value, an alert is signaled automatically by computer. Additional information on traffic conditions immediately upstream of the incident is then obtained, and judgment decisions are made as to what response is needed (*28*).

In FHWA Report No. 78-137 (*29*) are described guidelines and procedures for specifying the location and spacing of sensors needed and used by algorithms which detect freeway incidents. Some general guidelines indicate that station spacings over 2,500 ft produce unsatisfactory incident-detection algorithm performance. In contrast, decreasing the spacing below 1,000 ft generally produces relatively little or no increase in effectiveness while increasing the cost. For spacings between 1,000 and 2,500 ft, a cost-effectiveness trade-off occurs that varies among the following four types of geometric freeway sections:

- Freeways containing only level, tangential sections of roadway with on and off ramps
- Freeways containing weaving areas between 1,000 and 3,000 ft
- Freeway segments containing a change in the number of lanes
- Freeway segments with a change in the alignment

The cost procedures described can be used to determine the most effective cost for station spacing between 1,000 and 2,500 ft based on the users' requirements. Table 5.6 summarizes the results of the cost-effectiveness analyses performed in the report. In general, a partial-lane configuration performed as well as a full configuration. Therefore, from a cost-effectiveness viewpoint, the partial configuration is preferred (*29*).

Specific comments can be made for false alarm rates and placement of sensors relative to on/off ramps. For false alarm rates, the results show that rates increase when the station spacing is reduced to 500 ft. This further reinforces the recommended minimum station spacing of 1,000 ft. Evidence reveals advantages to locating sensor stations upstream of on-ramps and downstream of off-ramps.

The incident-detection system on the San Francisco-Oakland Bridge is being upgraded to include magnetic vehicle detectors in each of the 5 lanes at 1,200-ft intervals and optical queue detectors located at 600-ft intervals along the bridge. The optical queue detector will send a beam of infrared light transversely across all five lanes of the bridge. Since it was not practical to install or maintain loop detectors on the deck surface, system designers chose magnetic detectors secured beneath the bridge deck. Existing emergency pushbutton call boxes will supplement the main lane and queue detectors. The incident detection hardware and computer logic is designed to provide detection of stopped cars within one and a half minutes during medium and heavy traffic volumes.

192

5.5 FUTURE DETECTOR TECHNOLOGY

This section describes several new techniques of vehicle detection that are presently being considered or developed.

Self-Powered Vehicle Detector

The Self-Powered Vehicle Detector (SPVD) was developed by the Federal Highway Administration (FHWA) beginning in 1973 (*30*). The cylindrical detector has 4.5-in. diameter and 14.5-in. length. It contains a transducer and a RF transmitter with antennas and a roadside receiver. The power supply is two 6.75-v memory batteries with a 2-yr life expectancy at 20,000 vph. Calls can be transmitted at least 500 ft. Since no lead-in or interconnecting cables are needed, "this factor will reduce installation time and cost, reduce traffic disruption caused by vehicle-detector installation, and eliminate the lead-in cut or dig-up problems associated with the ILD" (*11*). The SPVD can measure vehicle passage, presence, count, and occupancy, with two SPVD systems obtaining speed accurately.

The SPVD has had several hardware revisions since its beginning. The current unit consists of the following:

- Transducer with a single, dual-axis Brown magnetometer
- RF transmitter which sends two 30-ms tone-coded pulses
- Receiver including a commercially available FM receiver and a tone decoder.

The transducer is oriented to detect changes in the horizontal and vertical components of the earth's magnetic field, similar to the standard magnetometer. A passing or stopped vehicle disturbs the earth's magnetic field, changing the operating level of the magnetometer's core. This change is sent to the roadside receiver via tone-code pulses.

The City of Kettering, Ohio, tested the SPVD detectors in 1979-1980 (*31*). One SPVD unit was installed in a left-turn lane, 118 ft from the receiver antenna. That unit operated flawlessly for the entire year of the test, despite temperatures sometimes approaching 0±F. A 12-month volume count comparison in the same traffic lane was performed between the operational SPVD and a standard 6-by-6-ft ILD. The SPVD produced a higher degree of accuracy in the test because the smaller zone of influence assured separate counts for closely following vehicles during times of congestion.

Table 5.6. Summary of cost-effectiveness freeway sensor placements for detecting incidents

Situation	Sensor Configuration	Sensor Spacing (Ft)
Mainline, 3 lanes	Partial	1,000-2,500
Mainline, 4 lines	Partial	1,000-2,500
Weaving 1,000 ft	Dependent on detection algorithm	1,000
Weaving 2,000 ft	Partial	1,000-2,500
Weaving 3,000 ft	Partial	2,500
Lane additions	Partial	1,000
Lane drops	Partial	500-1,000
Three percent grade alignment	Partial	1,000
Six percent grade alignment	Partial	1,000-2,500
Curve alignment	Partial	1,000-2,500

Source: Reference (*29*)

193

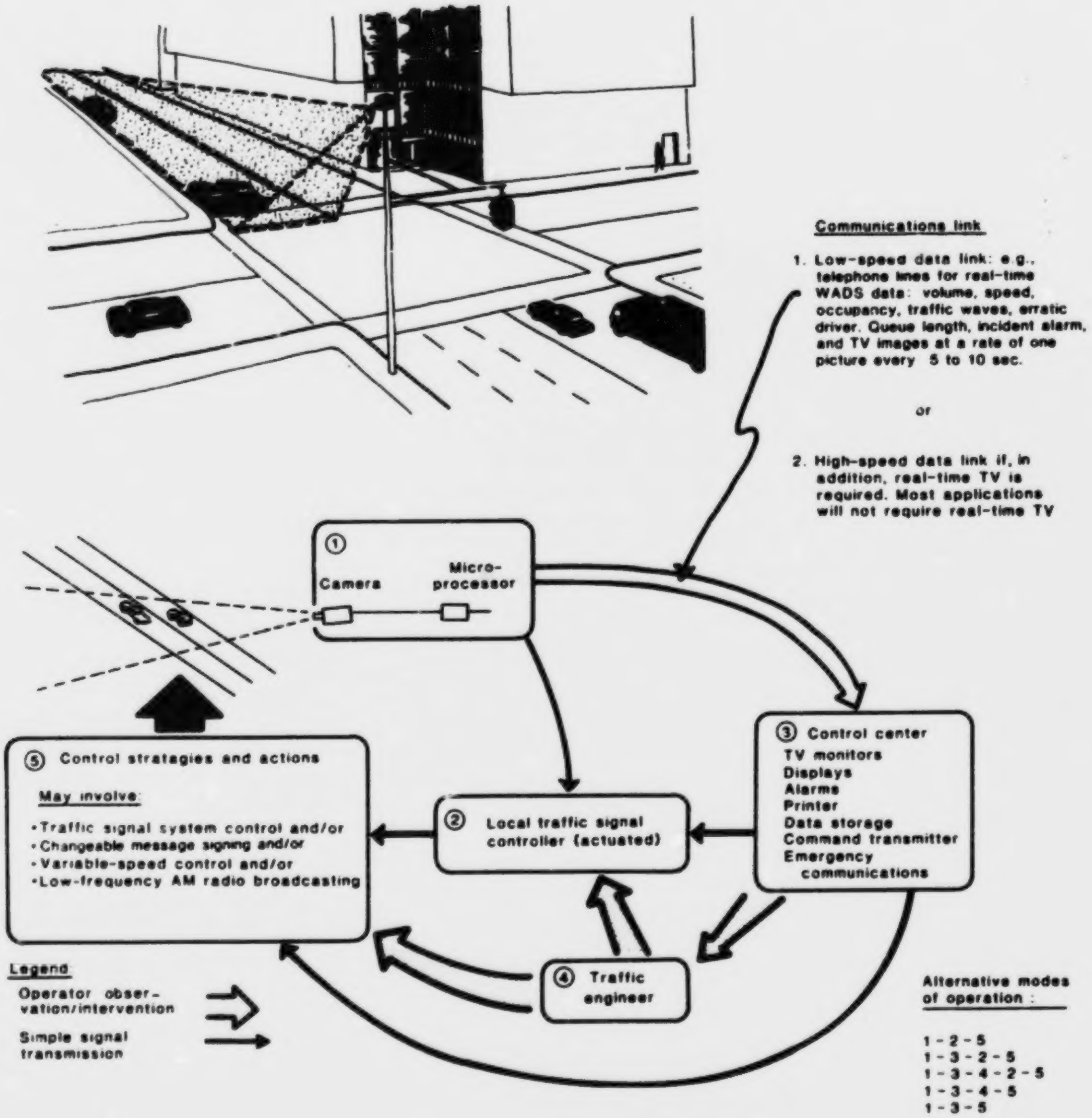

Communications link
1. Low-speed data link: e.g., telephone lines for real-time WADS data: volume, speed, occupancy, traffic waves, erratic driver. Queue length, incident alarm, and TV images at a rate of one picture every 5 to 10 sec.
or
2. High-speed data link if, in addition, real-time TV is required. Most applications will not require real-time TV
① Camera Micro-processor
③ Control center
TV monitors
Displays
Alarms
Printer
Data storage
Command transmitter
Emergency communications
② Local traffic signal controller (actuated)
⑤ Control strategies and actions
May involve:
•Traffic signal system control and/or
•Changeable message signing and/or
•Variable-speed control and/or
•Low-frequency AM radio broadcasting
④ Traffic engineer
Legend:
Operator observation/intervention
Simple signal transmission
Alternative modes of operation :
1 - 2 - 5
1 - 3 - 2 - 5
1 - 3 - 4 - 2 - 5
1 - 3 - 4 - 5
1 - 3 - 5

Figure 5.16. Control system options with Wide Area Detection System (WADS)

Source: Reference (*32*)

The City of Kettering estimated that the SPVD electronics and hardware could cost as much as $700 and still be no more expensive than the ILD on a first-cost basis. Over the long run, however, an SPVD at this price would show an economic advantage, because the replacement of batteries and an occasional radio transmitter would not approach the $400 cost of replacing the wire of a failed loop. The city concluded that the concept is cost-effective and worthy of further development.

Currently, 20 highway maintenance radio service frequencies in the 47 MHz band are available to operate the SPVD. A number of user agencies have expressed great interest in installing this unique device.

Wide Area Detection System (WADS)

The objective of the WADS project is to determine the technical feasibility of using television surveillance to automatically measure traffic parameters on mainline sections of urban freeways (*32*). The focus of current WADS effort is the automatic tracking of area measurements across several freeway lanes as well as along the traffic stream in each lane. In the measurement mode, WADS has the potential to determine lane density, speed, volume, queues, incidents, etc. As of 1982, WADS software had been tested in the field and confirmed to detect, track, and make traffic parameter measurements for vehicles in one traffic lane.

The WADS currently consists of real-time television, a microprocessor, and standard coaxial cable. One option to the hardware may be using slow-scan (compressed television transmission) equipment and low-speed data links (e.g. telephone lines). Using this option would reduce the communication cost considerably. Figure 5.16 illustrates the concept of control system options for this detection system. Although not fully tested, the WADS concept potentially offers advantages in a variety of applications.

REFERENCES

1. National Electrical Manufacturers' Association (NEMA). *NEMA Standards Publications for Traffic Control Systems.* TS1-1983, June 1983, p. 63.
2. Mills, Milton K. "Self Inductance Formulas for Multi-Turn Rectangular Loops with Vehicle Detector." May 27, 1983.
3. de Laski, Arthur B.; Alexander S. Byrne; and George S. Brisbin. *Traffic Detector Handbook.* FHWA-IP-85-1, Federal Highway Administration, Washington, D.C., 1985.
4. Dorsey, Warren F. *Status Report on Vehicle Detectors.* FHWA-RD-77-137, Offices of Research and Development, Federal Highway Administration, Washington, D.C., 1976, pp. 32-36.
5. "Blind Cross Street Safely in Bern." *Urban Transportation Abroad.* Spring 1983, p. 5.
6. Tarnoff, P. J.; A. M. Voorhees; and P. S. Parsonson. "Guidelines for Selecting Traffic Signal Control at Individual Intersections." Vol. II, National Cooperative Highway Research Program, American Association of State Highway and Transportation Officials, Federal Highway Administration, Washington, D.C., July 19, 1979.
7. Parsonson, Peter S., et al. "Small Area Detection at Intersection Approaches." Technical Committee No. 18, Southern Section, Institute of Transportation Engineers, *Traffic Engineering,* February 1974.
8. Parsonson, Peter S., et al. "Large Area Detection at Intersection Approaches." Technical Committee No. 17, Southern Section, Institute of Transportation Engineers, *Traffic Engineering,* June 1976.
9. Zegeer, C. V. "Effectiveness of Green Extension Systems at High-Speed Intersections." Research Report No. 472, Kentucky Department of Transportation, Bureau of Highways, Division of Research, Lexington, Kentucky, May 1977.
10. Sackman, Harold; Bruce Monahan; Peter S. Parsonson; and Albert F. Trevino. "Vehicle Detector Placement for High-Speed Isolated Traffic-Actuated Intersection Control." Vol. 2: *Manual of Theory and Practice.* FHWA-RD-77-32, Federal Highway Administration, Washington, D.C., May 1977.
11. Parsonson, Peter S. "Signalization of High-Speed, Isolated Intersections." *Transportation Research Board Record 737,* 1978, pp. 34-42.
12. Tarnoff, Phillip J. and Peter S. Parsonson. "Guides for Selecting Traffic Signal Control at Individual Intersections." National Cooperative Highway Research Pro gram Project 3-27, *Research Results Digest* 117, Transportation Research Board, Washington, D.C., February 1980.
13. Keim, John H. "Demand Control." Eagle Signal Division, E. W. Bliss Company, 1968. (Unpublished, mimeographed.)
14. Parsonson, P. S.; R. A. Day; J. A. Gaulas; and G. W. Black. "Use of EC-DC Detector for Signalization of High-Speed Intersections." *Transportation Research Board Record 737,* 1979, pp. 17-23.
15. "Design of Detection Loops Specifications." Section V, Illinois Department of Transportation, pp. 24-27.
16. *Traffic Detector Handbook,* Chapter 3.
17. *Traffic Engineering,* June 1976.
18. Pinnell-Anderson-Wilshire and Associates, Inc. "Management of Traffic Control Systems." Executive Course for the Federal Highway Administration, 1978.

19. *Computerized Signal Systems, Student Workbook.* Prepared for the Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., June 1979.

20. Haenel, Herman E.; Alfred K. Kosik; and Blair G. Marsden. "Innovative Uses of Traffic Responsive Control in Texas." Texas Department of Highways and Public Transportation, 1983, p. 46.

21. Kay, J. L.; R. D. Henry; and S. A. Smith. "Locating Detectors for Advanced Traffic Control Strategies." *Handbook*, FHWA-RD-75-91, Federal Highway Administration, Washington, D.C., 1975.

22. JHK & Associates. "Detector Location Plan for 1.5 Generation of Control," *System Specifications for Los Angeles ATSAC*, 1982.

23. Henry, R. D.; S. A. Smith; and J. M. Bruggeman. "Locating Detectors for Advanced Traffic Control Strategies." *Technical Report*, FHWA-RD-75-92, Federal Highway Administration, Washington D.C., September 1975.

24. Everall, Paul F. *Urban Freeway Surveillance and Control, State of the Art.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., November 1972.

25. Blumentritt, C. W., et al. *Guidelines for Selection of Ramp Control Systems.* NCHRP Report No. 232, National Cooperative Highway Research Program, Washington, D.C., May 1981.

26. Ross, Dale W. *Detectors, Communications Equipment and Computers for Traffic Surveillance and Control Systems.* Prepared for Short Course on "Urban Freeway Surveillance and Control: the State-of-the-Art," March 26-29, 1974.

27. Blikken, W. A. "The Adjustable Diamond Loop for Vehicle Detection." Michigan Department of Transportation, Detroit Freeways Operation Unit, 1979.

28. Capelle, Donald G. "Freeway Traffic Management." NCHRP Project 20-30, Transportation Research Board, Washington, D.C., September 1979, p. 24.

29. Koble, H. M., et al. *Formulation of Guidelines for Locating Freeway Sensors.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., December 1979.

30. Dorsey, Warren F. *Status Report on Vehicle Detectors.* FHWA-RD-77-137, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., November 1976, p. 3.

31. Oaks, Richard L. "Test of Self-Powered Vehicle Detectors." Kettering, Ohio.

32. Hilbert, E. E., et al. "Wide Area Detection System-Conceptual Design Study." FHWA-RD-77-86, Office of Research and Development, Federal Highway Administration, Washington, D.C., February 1978.

33. "Type 170 Traffic Signal Control System — Hardware Specification." FHWA-IP-78-16, Office of Research and Development, Federal Highway Administration, Washington, D.C., December 1978.

34. Haenel, Herman, et al. "A Standard for Vehicle Detector, Revised Standard." Technical Council Committee 4L-S, Institute of Transportation Engineers, 1981.

35. Wu, C. S.; Machemehl; Lee. "Detector Configuration and Location of Signalized Intersections." Report 259-1F, Center for Transportation and Research, University of Texas, March 1983.

36. Basu, S., and J. R. Wroble. *Computerized Signal System: Overview and Product Summaries,* FHWA-TS-82-218, Office of Safety and Traffic Operations Research and Development, Federal Highway Administration, Washington, D.C., 1982.

37. Kell, James H., and Iris S. Fullerton. *Manual of Traffic Signal Design.* Institute of Transportation Engineers, 1982.

38. Eagle Signal Division, Gulf and Weston Corporation. Diagram of a nondirectional, uncompensated magnetic detector (used in Figure 5.2).

39. Canoga Controls Corp., subsidiary of 3M Company. Diagram of magnetometer detectors (used in Figure 5.3).

40. SCANDI System. Specifications 1979 (used in Figure 5.15).

41. *Traffic Control Systems Handbook.* Federal Highway Administration, U.S. Department of Transportation, June 1976.

42. Tarnoff, Philip J. "The Results of FHWA Urban Traffic Control Research: An Interim Report." *Traffic Engineering,* Vol. 45, April 1975, pp. 27-35.

43. Honeywell, Inc. "Vehicle Detector — Phase III — Passive Bus Detection/Intersection Priority System Development," Volumes I-III. FHWA RD 76-66 to 68, inclusive. Federal Highway Administration, Washington, D.C., December 1975.

6. LOCAL CONTROLLERS

CONTENTS

Section — *Page*

6.1 INTRODUCTION 6.3

6.2 TYPES OF OPERATION 6.3

6.3 RANGE OF APPLICATIONS 6.5
- **Street Intersection Control** 6.5
  - ***Isolated Intersection*** 6.5
  - ***Arterial System*** 6.5
  - ***Network System*** 6.6
- **Special Controls** 6.6

6.4 HARDWARE EVOLUTION 6.7

6.5 TYPES OF LOCAL CONTROLLERS 6.8
- **Pretimed Controllers** 6.8
  - ***Electromechanical Controllers*** 6.8
  - ***Solid-State Digital Controllers*** 6.8
- **Full-Actuated Controllers** 6.8

6.6 PRETIMED CONTROLLERS 6.8
- **Timing Characteristics** 6.8
- **Hardware Characteristics** 6.9
  - ***Electromechanical Devices*** 6.9
  - ***Solid-State Devices*** 6.10
- **Coordination Requirements** 6.10

6.7 FULL-ACTUATED CONTROLLERS 6.10
- **Controller Operation** 6.11
- **Controller Detection Modes** 6.11
  - ***Locking Detection Memory*** 6.11
  - ***Nonlocking Detection Memory*** 6.11
- **Timing and Phasing Characteristics** 6.11
  - ***Single- and Dual-Ring Operation*** 6.12
  - ***Basic Interval Timing Functions*** 6.12
  - ***Special Operational Features*** 6.13
- **Hardware Characteristics** 6.17
  - ***Environmental and Operating Requirements*** 6.17
  - ***Conflict and Voltage Monitor*** 6.17
  - ***External Logic Devices and Software Logic (Special Logic)*** 6.17
- **System Capabilities** 6.20
- **Down-Loading Capabilities** 6.20

Section *Page*

6.8 MODEL 170 AND NEMA CONTROLLERS 6.21
Model 170 Controllers 6.21
Software Programs 6.23
Local Intersection Program (LIP) 6.23
Isolated Traffic-Actuated Program (ITAP) 6.23
Diamond Interchange Program (DIP) 6.24
Basic Arterial System (BASYS) 6.26
NEMA Controllers 6.26
Comparison of NEMA and Model 170 Controllers 6.26

6.9 LOCAL CONTROLLER COORDINATION 6.28
Function 6.28
Forms of Interconnection 6.29
Physical 6.29
Air-Path Communication 6.29
Time-Base Coordination 6.29

6.10 FACTORS IN CONTROLLER SELECTION 6.30
Operating Requirements and Constraints 6.30
Anticipated Effects and Costs 6.31
Maintainability and Reliability 6.31
Implementability and Flexibility 6.31
Human Factors 6.32

REFERENCES 6.32

6. LOCAL CONTROLLERS

6.1 INTRODUCTION

In the discussion of local control equipment in this chapter, two phrases used extensively are defined as follows:

- Controller assembly — The complete electrical mechanism mounted in a cabinet for controlling the operation of a traffic control signal. Unless excluded specifically, the cabinet is also generally considered to be included in the controller assembly.
- Controller unit — That portion of a controller assembly that is devoted to the selection and timing of traffic signal displays.

Local controller units are classified into the following general types:

- Intersection controller units define the traditional and original usage, most commonly referred to as traffic signal controllers.
- Special controllers include those units used for freeway control and surveillance, lane-use control, and other applications not involving the traditional assignment of right-of-way for vehicles and pedestrians at intersection or midblock locations.

The local controller unit is utilized to control a midblock crosswalk, a single intersection, or closely spaced multiple intersections. The primary function of an intersection controller unit is the electrical switching of the signal indications (red, yellow, green, WALK, DONT WALK, etc.) to assure that appropriate right-of-way assignments are fulfilled in accordance with predetermined or traffic-demand time intervals. Certain intervals used for pedestrian and vehicle clearances, such as flashing DONT WALK and red clearance intervals, are always of predetermined duration. Greens and green arrows are of fixed duration in the case of pretimed control, but they are literally timed by traffic demand (up to a predetermined maximum) in actuated intersection control. Although the timing described is a normal function of the intersection controller unit, if the unit is under system supervision, a central computer or master controller may be the device which actually determines or alters the timing of certain intervals at the local intersection.

Intersection controller units are classified by two distinct modes of operation:

- Isolated control, in which the local controller acts as a stand-alone unit and times the assignments of right-of-way independently, unaffected by other devices.
- Supervised local control, in which a device or devices, ranging from a time-base coordination unit to a remote master controller or central computer, determine or alter interval durations and/or maintain timing relationships in a group of local controllers. Under supervised local control, the local intersection controller units may either be part of an arterial or grid network system or simply be a small system comprised of two local units in which one of the controllers acts as a supervising master and as a secondary controller.

Special controller units and their range of application are discussed briefly in a subsequent section of this chapter. (See also Chapters 3 and 4 of this Handbook for additional information on some of the special control concepts.)

6.2 TYPES OF OPERATION

Despite the many variations in their design, intersection controller units can be described as follows:

- Pretimed operation — The duration of all intervals is predetermined, with interval timing handled by the local controller unit at an isolated intersection. Under supervised control, the duration of certain intervals is determined by a master controller or other remote device. The operation and characteristics of pretimed control are discussed in detail in subsequent sections of this chapter.
- Full-actuated operation — All signal phases are actuated, and the change and clearance intervals are of predetermined duration. The length of each of the respective variable intervals, such as greens and green arrows, is determined by the local controller unit based on detected traffic demand on the associated approach, and is limited by the preselected maximum timing set in the controller. Phase-associated WALK intervals are of a guaranteed duration, but are timed and displayed only upon respective pedestrian pushbutton actuation. Operation and characteristics of full-actuated control are discussed in detail in subsequent sections of this chapter.

199

- Semiactuated operation — Controller units operating in the semiactuated mode provide a guaranteed minimum green time for the nonactuated, major street phase. The green interval on the major street is relinquished only when a conflicting call is received on the actuated phase(s). After timing the appropriate major street change and clearance intervals, green is displayed to the calling phase for the minimum green interval. The phase being serviced will retain right-of-way as long as vehicles are detected and the vehicle (passage) interval portion is reset. The actuated phase green interval will terminate when the vehicle passage time is allowed to time out, when the maximum green time has been reached, or when force-off is applied. The change and clearance intervals are timed and green is displayed to the next calling phase for the minimum green interval (in the case of multiple actuated phase operation), or green for the nonactuated major street phase is displayed (2-phase operation) (*1*).

Semiactuated control has the following characteristics:

- Detectors are located only on actuated-phase approaches.
- Nonactuated phase receives minimum green interval.
- Nonactuated phase green extends indefinitely until interrupted by actuation on other phases.
- Actuated phase receives green upon actuation provided that the nonactuated phase has completed its minimum green interval.
- Actuated phase has a minimum green interval.
- Additional vehicle calls will extend actuated phase green until the preset maximum is reached or a gap in actuations exceeds the unit extension (passage) interval portion.
- If locking detection memory is used on the actuated phase, additional actuations will be remembered if the maximum is reached, and the controller will reservice the actuated phase after nonactuated phase minimum green is reached.
- Yellow change and red clearance intervals are preset for each phase (*1*).

In semiactuated operation it is desirable to minimize delay on the major street by using the shortest practicable timing settings for intervals on the actuated phase(s) (*1*).

Limitations inherent in semiactuated control have led many traffic engineers to feel that this type of control has limited application. Example applications include mid-block and T-intersection pedestrian crossings, typically located within a signal network.

- Volume-density full-actuated operation — Full-actuated controller units operating in the volume-density mode are programmed to operate with an added initial interval and a reducible gap feature in addition to the timing features of the basic full-actuated unit. Certain phases are selected for this type of operation and left-turn phases are not usually included. Volume-density features vary the amount of time a phase will receive the green interval based upon a more complex evaluation of traffic conditions on the subject approach. The maximum extension of green for a phase, however, functions in exactly the same manner as that for the basic full-actuated controller unit (*1*).

With volume-density control, detectors may be placed farther from the stop line. When a single-point source detector is used, the initial interval is normally the time required for a standing queue of vehicles between the detector and the stop line to start moving through the intersection. To avoid long minimum green intervals, a volume-density controller unit counts the number of vehicles arriving during the yellow and red intervals and expands the minimum green interval accordingly. One of three different techniques can be employed to effect minimum green interval expansion:

- ☐ Added initial timing — This timing technique adds time to the minimum green interval portion based on time increments derived per vehicle from the number of actuations counted. Minimum timing is used as set in the controller unit until a preset number of counted actuations is reached. When that number is exceeded, the minimum green interval is expanded accordingly.
- ☐ Computed initial timing — This technique uses a preset minimum and maximum timing. The minimum green interval is expanded (up to the preset maximum) based upon a preset number of vehicles which are detected during the period.
- ☐ Extensible initial timing — This method is similar to the computed initial technique except that the minimum green interval is expanded (up to a preset maximum) based upon preset time increments per vehicle detected during the period (*1*).

In addition to variable minimum green interval timing, gap-reduction timing is also used in volume-density operation. The effect on the extensible (gap-reduction) portion of the timing is to reduce the allowable gap between successive vehicle actuations by decreasing the extension time in a manner dependent upon the time waiting of vehicles on an opposing phase. The following functional settings are used in gap-reduction timing:

- Time before reduction — This period begins in the green interval when a serviceable conflicting call occurs. If the serviceable conflicting call is withdrawn while timing in this period, the timer is reset and remains so until the next serviceable conflicting call. Upon completion of this period, the linear reduction of the allowable gap begins.
- Passage time, minimum gap, time to reduce — The rate of reduction is based on the setting of these three controls. The allowable gap is reduced at a rate equal to the difference between the passage time and minimum gap settings, divided by the setting of the time-to-reduce control. Thus, the reduction of the allowable gap continues until the gap reaches a value equal to, or less than, the minimum gap control setting, after which the allowable gap remains fixed. In the presence of a continuous vehicle actuation, the phase does not gap out even if the minimum gap is set at zero. If at any time the serviceable conflicting call is withdrawn, the gap length returns to passage time setting, and the time before reduction timer is reset to remain so until the next serviceable conflicting call.

Volume-density-type control has the following characteristics:

- Detectors are located on all approaches.
- Each volume-density phase has minimum green interval time that can be varied by added initial, computed initial, or extensible initial.
- Vehicle extension interval is the extended green time created by each additional actuation after the minimum green interval time has elapsed.
- In the presence of an opposing call, the vehicle extension interval is reduced to a minimum gap after a preset time.
- Maximum green or extension limits are preset for each phase.

Volume-density, full-actuated control is usually effective at intersections where high speeds or high volumes are found. Detectors must be carefully located and proper timing settings must be used, however, to achieve efficient and safe traffic control. Most full-actuated controller units currently manufactured are capable of volume-density type operation (*1*).

6.3 RANGE OF APPLICATIONS

Street Intersection Control

Isolated Intersection. Intersection control at an isolated location involves a signal installation independent of the operation of any adjacent control. Roadway characteristics, such as the number of approach lanes, traffic volumes, arrival patterns, and number of intersection approaches are all factors used in determining the appropriate type of intersection control (*2*).

Pretimed control is best suited for locations where traffic is highly predictable and constant over a long period of time. These situations do not usually exist at isolated intersections (*2*).

Full-actuated control is usually the most efficient type of operation at isolated intersections. Once the decision is made to install a traffic signal, full-actuated control should be the first consideration. The traffic-responsive capability of this type of control varies the cycle length and phase lengths (split) on a micro basis, so that these 2 controller timing elements are adjusted from cycle to cycle to fit the changing demands. Rarely are approach traffic volumes at an isolated intersection predictably constant over a long period of time. Because all phases usually do not peak at the same time at isolated intersections, it is not valid to assume that a full-actuated signal operates on a fixed cycle length even with high traffic demand.

Full-actuated control is applicable to a variety of signal phasing and detectorization schemes ranging from a simple 2-phase operation to 8-phase dual-ring configuration. To emphasize the versatility involved, the 8-phase dual-ring controller may operate as a basic 2-phase controller under light traffic conditions, because of its skip-phase capability. If demand is not present, the phase is ignored, and the controller unit continues around the ring seeking a serviceable phase (*2*).

Single-intersection control is not limited to the intersection of 2 or more streets. Pedestrian signal control may be located midblock when a pedestrian crossing cannot be supplied (or is impractical because of the distance) at an adjacent, signalized street intersection. Control may also be warranted at intersections or midblock locations to give emergency vehicles access to a major street (*2*).

Arterial System. Intersection control in an arterial system is comprised of 2 or more traffic signals whose operation is time-related. Any of the above previously described types of signal operation may be employed at the local control level in an arterial system. The major concern in this control plan is supervision of local controllers along an arterial street to ensure progressive traffic flow. The basic concept of arterial street control is that vehicles on the arterial are released in platoons and travel progressively from signal to signal with little or no impediment. Depending upon prevailing traffic demand, this progression may be oriented to one or both travel directions. The main objective is to establish and ensure a time relationship between the beginning of arterial greens at each of the locally controlled intersections commensurate with progressive flow speed and desired direction, so that continuous traffic flow in defined platoons reduces stops and delay.

Network System. In a network system, crossing arterials, such as a typical central business district (CBD), form a grid pattern with virtually every intersection in the network requiring local signal control. Because of the nature of this closely spaced arrangement of signals and a basic desire to provide arterial progression on all of the streets in each travel direction, prevalent local control is pretimed operation.

Semiactuated control is used in some network systems at midblock pedestrian signals and, less often, at lighter traveled T intersections to provide left-turn protection on demand only. As in the arterial system, the objective in the network system is to provide time relationships between the beginning of greens at each of the locally controlled intersections. The relationship is defined by a timing plan designed to optimize traffic performance for a given traffic pattern (inbound peak, balanced light flow, etc.).

Table 6.1 shows applications of the various types of street intersection control.

Special Controls

Special-purpose controller assemblies are used in a number of applications, and, although the electrical switching of signal indications makes them akin to intersection controllers, they should be discussed separately. Some of the applications include the following:

- Flashing beacons for various applications such as roadway hazard identification, enforcement time definition for speed limits, intersection hazard identification with stop control, and a visual-attention device with individual stop signs
- Lane-use control signals
- Movable bridge signals and one-lane, two-way operation signals
- Traffic signals at freeway entrance ramps

Only lane-use control signals and signals at freeway ramps will be discussed here. Reference is made to the *Manual on Uniform Traffic Control Devices* (MUTCD)

Table 6.1 Range of applications to street intersection control

Type of Control	Isolated Intersection	Arterial System (Open Network)	Network System (Closed Network)
Pretimed	Usually not appropriate	Could be applicable if cross street carries consistent substantial traffic volumes	Prevalent type used
Semiactuated	Usually not appropriate unless side street volumes are less than 20 percent of those on major street	Applicable for intersections with lighter cross street volumes. Also used at midblock pedestrian crossings	Sometimes used at midblock pedestrian crossings
Basic full-actuated	Most widely used control type for isolated intersections; use ranges from Sample 2-phase through dual-ring 8-phase configuration	Applicable for high-type intersection with heavy, fluctuating demand which requires multiple phasing on cross street	Not applicable because of relatively short block spacing and high, predictable volumes on all streets
Volume-density	Provide greatest benefit with approach speeds above 35 mph or where detector setback exceeds 125 ft	Sometimes applicable when volume-density concept is limited to use on major street	Not appropriate

Source: Reference (2)

(*3*) for further information on design and all of the special controls listed.

Lane-use control signals are special overhead signals having indications to permit or prohibit the use of specific lanes of a street or highway or to indicate the impending prohibition of use. They are most commonly used for reversible-lane control, but they may be used where there is no intent or need to reverse lanes such as on a freeway where it is desired to keep traffic out of certain lanes at certain hours or to indicate that a lane ends (*3*).

Reversible-lane operation is used to increase arterial roadway capacity during periods of directional peak traffic flow. Current techniques utilize a combination of overhead signals and signing. The signals consist of a red X on an opaque background or a green arrow (pointing down) on an opaque background. A yellow X may also be used, with only one of the three indications displayed at a time per lane, per direction.

Operation mode changes are usually done on a time-of-day basis commensurate with peak traffic demands. Control equipment consists of switching equipment, electrically or mechanically interlocked, to prevent conflicting display, and appropriate clock/switch devices. Some of the longer distance systems (of several miles or more) utilize progressive lane vacation, whereby overhead indications are switched individually or in small groups in directional patterns along the arterial. This operation minimizes the possibility of vehicle conflicts which might occur if all common indications in the system were abruptly switched. Lane use control should be used only when an engineering study verifies the need and practicability, and safe operation can be assessed (*3*).

Traffic signals at freeway entrance ramps are typically installed to control the rate of flow of entering traffic. For complete ramp closure, automatic or manually placed barriers are used in conjunction with a ramp-type signal to effect the desired results.

Chapter 4 contains a discussion of freeway entrance ramp control and surveillance techniques.

6.4 HARDWARE EVOLUTION

Clearly, the evolution of traffic signal controller hardware parallels that in related industries. Undoubtedly, the phenomenal pace in electronics development during the past 20 years in all fields has been spurred by innovation and miniaturization required in the space industry. Signal controller unit hardware has evolved from the motor-driven dials and camshaft switching units to the adaptation of general-use microprocessors for a wide variety of intersection-control and special-control concepts.

In the early years of traffic signal control, virtually the only commercially available controller units were the electromechanical type. Later, several manufacturers introduced semiactuated and full-actuated controllers which were equipped with vacuum tube-type electrical circuitry for timing functions. The traffic engineer was introduced to interval and phase timing, adjustable via knobs on a control panel. The transformers and vacuum tubes in these analog-type units generated considerable heat, initiating requirements for forced-air circulation and filtering in controller cabinets. Some manufacturers retained solenoid-driven camshafts for lamp switching hardware, while others utilized stepping relay-driven stacked rotary switches and encapsulated relays for this purpose. Short component life and timing drifts were characteristics of these controllers.

The introduction of the transistor as a functional replacement for the vacuum tube heralded the use of low-voltage circuitry with only a fraction of the former heat generation. High-amperage heater circuits and high-voltage B plate circuits required for vacuum tubes had passed from the scene. During the mid-1960s, transistorized circuits were first used for timing and phasing functions in traffic control. Lower operating temperatures, increased component life, and digital timing assured timing accuracy and eliminated fluctuations. Also introduced during this period was the solid-state load switch for lamp circuits. A wide range of component and equipment arrangements from manufacturer to manufacturer also was prevalent during the 1960s. Designs varied from all timing and phasing components placed on a single circuit board to modular, plug-in phase and function-oriented designs.

The next major step in the evolution process was the development of the integrated circuit (IC). Microchip technology had shrunk components, literally, to microscopic size in some cases. These very small chips were then linked together in circuits and sealed within an IC envelope. Today hundreds, even thousands, of solid-state devices can be made part of an IC which is smaller than a postage stamp. This technology made the microprocessor a reality. Previously, a computer was a large and environmentally sensitive unit. The advent of the microprocessor led to the development of microcomputers — small, lightweight, low-cost units seen everywhere today.

Microprocessors were quickly incorporated into new signal controller designs by the industry. They are, today, the heart of solid-state controller units, both the pretimed and the full-actuated types.

203

6.5 TYPES OF LOCAL CONTROLLERS

This section categorizes local controller units as pretimed and full-actuated controllers. While volume-density-actuated and semiactuated controller units are recognized as variations of actuated control, the subsequent discussion in this chapter will be limited to these two major controller operational concepts.

Pretimed Controllers

Electromechanical Controllers. The oldest type in use, electromechanical controllers constitute a very significant percentage of all controllers in service in the United States today. These units consist of a synchronous motor which drives timing dials and, in turn, advances a solenoid-operated or a motor-driven camshaft for signal lamp switching. Simple in design, these units were, until the advent of solid-state electronics, virtually the only type of controller commercially available. Substantial numbers of these electromechanical controllers are still manufactured and sold each year.

Solid-State Digital Controllers. The pretimed solid-state digital type of controller provides the same timing and switching concept as the electromechanical type, but utilizes state-of-the-art hardware components. Characterizing these controllers are integrated circuitry, solid-state load switching, and entry of cycle and interval timing by thumbwheel, plug-in pins or keyboard. Slowly, the digital pretimed controller is gaining acceptance as a replacement unit for the electromechanical type and for use in new signal installations. Many of these units are sized and designed for replacement of electromechanical controller units in existing cabinets.

Full-Actuated Controllers

NEMA controllers are solid-state, full-actuated-type units manufactured in accordance with standards published by the National Electrical Manufacturers Association (NEMA), 1983 (*4*). The standards cover the following:

- Definitions for functions and hardware
- Environmental requirements and test procedures
- Interface requirements
- Physical and functional requirements
- Peripheral equipment to complete the controller assembly, such as load switches, conflict monitor, detector amplifiers, flasher switches, electrical terminals and facilities, and power supply

NEMA standards cover full-actuated operation ranging from 2-phase to 8-phase, with overlaps.

Model 170 controllers are general-purpose, microprocessor-based units manufactured in accordance with the Model 170 specifications (*5*). The specifications were jointly developed by the states of California and New York, in cooperation with the Federal Highway Administration (FHWA); but, unlike NEMA Standards, the Model 170 specifications do not cover control functions. Each manufacturer designs controllers in accordance with the specifications. The concepts of the states of California and New York are to purchase the controllers directly from the manufacturer and to then add the necessary discrete software to respective units for implementation of desired control functions. Software for the Model 170 controllers can also be provided and integrated with respective controller units by consultants, or suppliers, or by the manufacturer with the controller. The Model 170 specifications do not cover the software necessary for implementation.

If appropriate software is installed, the Model 170 controller will functionally duplicate NEMA units. Those familiar with the Model 170 software, who are adept in programming and possess the necessary simulation equipment, may also be able to modify standardized versions of the Model 170 software to accommodate a variety of traffic control applications.

6.6 PRETIMED CONTROLLERS

Timing Characteristics

Pretimed controllers operate on predetermined, fixed intervals and phase timings. The number and sequence of right-of-way assignments (phases) and the cycle length are also fixed. These timing features do not, however, make the pretimed controller completely inflexible. Each set of predetermined time increments described above applies to a single dial or timing plan used in the controller. In solid-state units, the cycle length, phase split, and/or phase sequencing can be changed by selecting a different timing plan. The timing plan or dial in use can be changed internally within the controller assembly by time clock or time-base coordinator, or, externally, by a remote device supervising the controller.

Another timing element enters the picture when the pretimed controller is part of a coordinated or otherwise supervised system. Offset timing represents the relationship in a given cycle frame of two or more local controllers, usually referenced from the beginning of the green interval on the street common to each of the system intersections. This offset timing relationship can be from one signalized intersection to an adjacent intersection, or can be expressed as one intersection's point of offset, per current system (cycle length) time frame.

Hardware Characteristics

Electromechanical Devices. A previous section of this chapter outlines electromechanical controller operation. The following is a detailed description of hardware components used in these type of units.

The following devices comprise an electromechanical controller:

- The dial unit, consisting of synchronous motor, manually changeable cycle gear, the dial, timing keys, and a bank of key-operated switches, all as shown in Figure 6.1
- The camshaft or switching drum, consisting of a solenoid or motor for incremental rotation, individual cams with appropriate switch breakouts, and a bank of switch contacts for lamp circuits and other dial/camshaft mutual functions, all as shown in Figure 6.2

The dial unit provides the timing for intervals selected for use at the intersection. Pretimed controllers generally come equipped with one to three dial units. Three dial units give the capability of using three different cycle lengths, one each for the a.m. peak, the p.m. peak, and the off-peak period.

The principle of operation of the dial unit is that the dial motor rotates the cycle gear, which in turn rotates the dial drum. The timing keys are placed in the slotted drum, which is graduated in one percent increments. Timing keys serve to mark the beginning of the red, yellow, green, etc., intervals for each phase. Cycle gears, which determine the total cycle length, are normally available in 5- or 10-sec increments from 30 to 150 sec. In the typical dial unit, the camshaft impulse key serves to rotate the cam to the next timing interval (i.e., Phase 1 green, Phase 1 yellow, Phase 1 red, etc.). The camshaft release key operates a switch that provides for the synchronization of the cam and dial. Offset keys are used to establish the offset relationship between intersections.

The other basic part of the signal timing unit is the camshaft or drum. This unit is activated by the timing keys and rotates to cause the signal indications to change. As the timing key reaches the 12 o'clock position on the dial, it activates the camshaft impulse switch and causes the camshaft to rotate one position. The cams, which are broken out to allow a contact arm to drop into a slot in the cam, either actuate relays (which change the signal indications) or change indications by direct contact. Some controllers use cam inserts instead of breakouts.

Multiple-dial pretimed controllers have extra keys to initiate the transfer from one dial to another. Each dial can be equipped with 3 splits and 3 offsets. Thus, a 3-dial controller is capable of providing 3 different cycle lengths, 3 sets of splits and 9 different offsets (3 offsets per dial); 3 splits are provided for each of the 3 dials on some controller units.

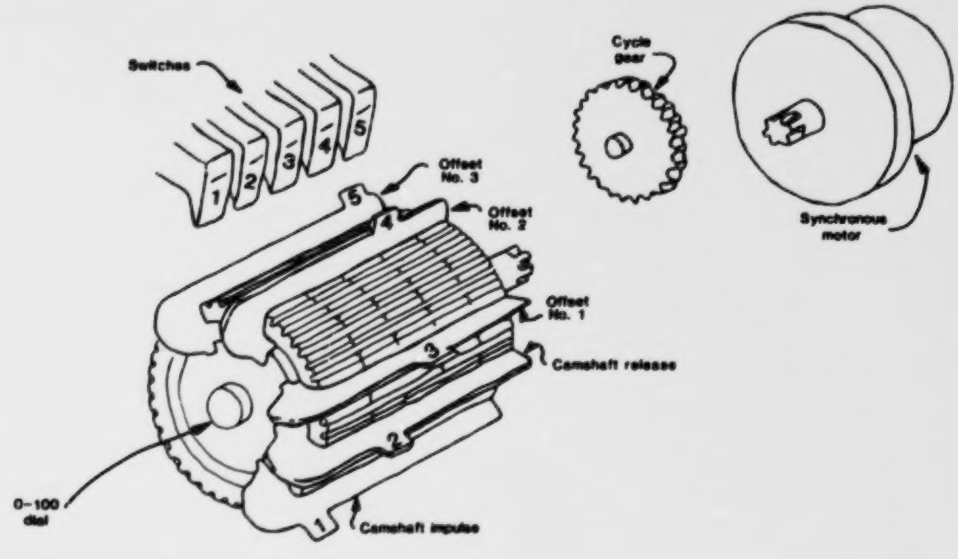


Figure 6.1. Typical dial unit

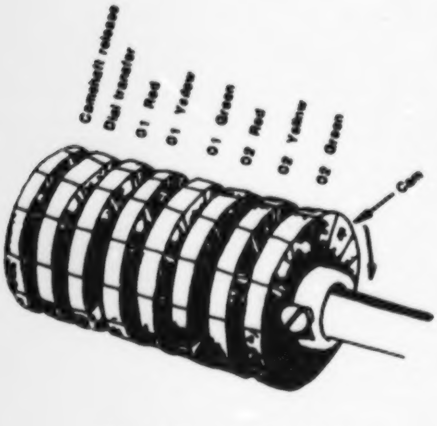


Figure 6.2. Typical camshaft

Solid-State Devices. The solid-state version of the pretimed controller employs microprocessor technology and complementary metal oxide semiconductor (CMOS) logic circuitry to perform the functions associated with synchronous motors, dial units, and switching cams in electromechanical controllers. Time reference is established by digital counting of the 60-cycle power line frequency. Signal timing is stored in random access memory (RAM), which is usually battery-backed, so that timing can be retained in case of power failure. Timing information input is usually via keyboard entry. Other program data and the program which operates the controller are resident in programmable read-only memory (PROM).

One of the advantages of solid-state controllers is that capabilities not ordinarily found in electromechanical units can be easily incorporated by utilizing the microprocessor. Some of the features include the following (*1*):

- Time-base coordination
- Programmable preemption sequences
- Capability to program specific output circuits to be ON, OFF, or FLASH during each interval
- Alternate phase sequencing
- Detector actuation input for phase selection
- Selection of different offset seeking techniques

Since the unit is solid-state, additional auxiliary equipment is required. The interlock for signal displays, inherent in the electromechanical camshaft, now is assured by a conflict monitor. The low DC voltage used in solid-state controller units mandates the use of load switches for 110-v lamp circuits. Timing modifications and maintenance are relatively easy, and the initial cost of the solid-state unit is comparable to that of electromechanical controllers (*1*).

Coordination Requirements

The pretimed controller is widely used in both open and closed network systems. The system operation of electromechanical-type controllers may be attained in one of the following two ways:

- The first uses synchronous operation of the dial motors in local units in the system, maintained manually through use of a stopwatch. Provided there is no local power failure or controller malfunction, the controllers within the system will remain in the same offset relationship. However, power failures do necessitate manual dial resets.
- The second method, the one most frequently employed, links the local controllers in the system together with a multiconductor cable. A master controller or master secondary controller establishes the coordination (sync) pulse for all controllers in the system. Other functions, such as dial transfer and offset selection, occur in the master controller by time-clock schedule and are transmitted via the multiconductor cable to each local controller. Thus, one conductor is required for each of the following system functions: ground (-), dial transfer 2, dial transfer 3, offset 1, offset 2, offset 3, flash, and system sync pulse. Some systems may not be equipped with all these functions listed. Sync and offset selection functions are handled via the dial switches on both master and local controller units. In some systems the sync pulse is imposed upon the respective offset conductor used, thereby negating the need for a separate conductor for sync pulse.

The above described multiconductor coordination system is compatible with solid-state pretimed controllers. Selectable phase sequences are also available for master control of solid-state locals. Implementation of additional functions would, of course, require a master unit of appropriate design to supervise the system and any additional cable conductors. State-of-the-art interconnect of solid-state pretimed controllers is accomplished through telephone wire pairs or other communication media, and modular-type, Time-Division Multiplexing/Frequency-Shift Keyed (TDM/FSK) modems.

6.7 FULL-ACTUATED CONTROLLERS

Modes of operation, controller characteristics and features covered in the following subsections are common to Model 170 and to NEMA controllers. Subsequent sections of this chapter describe attributes of each of the respective types of full-actuated controllers.

Controller Operation

A full-actuated controller unit provides for variable vehicle green intervals with operator-selectable pedestrian interval(s), phase sequences, and durations which reflect respective traffic approach volumes or the presence of pedestrians. The timing of certain intervals and phase durations are determined (up to respective maximum times set in the controller) by outputs from vehicle detectors strategically placed in the roadway. The display of pedestrian indications depends upon respective pedestrian actuation of pushbuttons.

The two other types of actuated control operation, previously covered at the beginning of this chapter, are the semiactuated and the volume-density, full-actuated modes.

Controller Detection Modes

Locking Detection Memory. In this mode of operation, the detection of a vehicle is retained by the controller unit for future utilization when the detector amplifier output ceases near the end of green or during the yellow change, red clearance, or red displays for the respective approach. Typically, small area detectors are placed in advance of the stop line on through-movement lanes of the major street approaches, and at (or near) the stop line for left turn lanes and minor street approaches. Vehicle actuations are thus locked into the controller for subsequent service of the called phase. This type of detection memory, however, creates difficulties in screening out false calls which may occur, for instance, in a right-turn-on-red situation from the minor street.

Nonlocking Detection Memory. In the nonlocking mode, the detection of vehicles is based on current occupancy of the detected field. Large area detection, i.e. long loops or a set of smaller loops wired in series to the same detector channel, and extending upstream from the stop line are necessary for proper operation. Thus, the continued presence of a vehicle within the detected field is required to extend the green interval or to call the respective phase. This mode provides for an increased sharpness in phase timing and the initial and vehicle extension (passage) interval settings can be adjusted to much shorter durations. Delay is reduced by screening out false calls to the controller unit, and the shorter time settings provide for faster transfer of right-of-way from phase to phase, particularly during periods of lighter traffic. The length of respective detection zones (loop length) is directly related to approach speeds and vehicle extension timing. Since higher approach speeds require a longer zone, the expected longer gaps between vehicles are detected and right-of-way maintained. When approach speeds reach 35 mph and greater, other detection design techniques should be employed. Chapter 5 of the Handbook explains the interrelationships between controller units and types of detection of both low-speed and high-speed approaches.

Timing and Phasing Characteristics

Full-actuated operation requires detectors on all approaches assigned, respectively, to each controller unit phase. Unless one of the recall features is set, or red rest is set for the respective ring, the full-actuated controller, in the absence of calls on opposing phases, dwells in the green interval of the last serviced phase. Activation of one of the recall features causes the controller unit to return and to service the designated phase even in the absence of detector actuations. The controller can also be set to dwell (red rest), in the absence of demand from any of the phase detectors, in an all-red state.

Maximum green time on a respective phase does not begin timing until there is a serviceable conflicting detector call. Therefore, a phase with continuing demand may remain green for some time before a conflicting call is registered that starts timing the maximum green. Depending on the duration of the continuing detector actuations for the active phase, the controller unit may, upon receipt of opposing detected demand, respond as follows:

- Immediately begin the sequence to serve the opposing phase, if opposing demand coincides with the termination of demand on the phase currently being served.
- Immediately begin timing maximum green, and with continuing demand on the phase currently being served, begin the sequence to serve the opposing phase only when the maximum green times out.

The timing and phasing characteristics of full-actuated controller units are summarized as follows:

- Each phase has a preset minimum green interval to provide starting time for standing vehicles.
- The green interval is extended for each additional vehicle actuation after the minimum green interval has timed out, provided that a gap in traffic greater than the preset unit extension setting does not occur.
- Green extension is limited by a preset maximum limit. Two selectable maximum limits (commonly referred to as MAX I, and MAX II) are provided on all NEMA-type controller units.
- Yellow change and red clearance intervals are preset

for each phase. Red clearance is not always needed in controller unit operation.

- Each phase is provided with a means of placing a call for minimum, maximum, or pedestrian recall.

Single- and Dual-Ring Operation. Several generic terms which are associated with the fundamental operation of full-actuated controller units, are basic to an understanding of the different types of controller operating modes. These terms, defined in the NEMA Standards, which are common to the operation of both Model 170 and NEMA-type controller units, are summarized as follows:

- Single-ring controller unit — A controller unit containing two or more sequentially timed and individually selected conflicting phases so arranged as to occur in an established order. The phases within a ring are numbered as illustrated in the examples in Figure 6.3.
- Dual-ring controller unit — A controller unit containing two interlocked rings which are arranged to time in a preferred sequence and to allow concurrent timing of respective phases in both rings, subject to the restraint of the barriers (compatibility lines). Each of the respective phase groups must then cross the barrier simultaneously to select and time phases in the phase group on the other side. The phases within the two timing rings are numbered as illustrated in Figure 6.4.
- Barrier (compatibility line) — A reference point in the designated sequence of a dual-ring controller unit at which both rings are interlocked. Two reference points or barriers (one for each phase group) assure that conflicting phases will not be selected or timed concurrently. Both rings (in one phase group) time out and then cross the barrier simultaneously, as illustrated in Figure 6.4.
- Dual entry — A mode of operation in a dual-ring controller unit in which one phase in each ring must be in service. If a call does not exist in one of the rings when the barrier is crossed (from the other phase group), a phase is selected in that ring to be activated by the controller in a predetermined manner. For example, referring again to Figure 6.4, in the absence of calls on Phases 7 and 8, Phase 2 and Phase 6 terminate to service a call on Phase 3. Programming for dual entry determines whether Phase 7 or Phase 8 will be selected and timed concurrently with Phase 3, even though no call is present on either Phase 7 or Phase 8.
- Single entry — A mode of operation in a dual-ring controller unit in which a phase in one ring can be selected and timed alone when there is no demand for service in a nonconflicting phase on a parallel ring. For example, referring to Figure 6.4, after the termination of Phase 2 and Phase 6, the controller unit will service a call on Phase 3 in the absence of calls on either Phase 7 or Phase 8. While Phase 3 is selected and timed alone, Phases 7 and 8 (in Ring 2) will remain in the red state.

Basic Interval Timing Functions. Full-actuated controllers units provide the following timing settings per phase:

- Minimum green interval — The first timed portion of the green interval which is set in consideration of the storage of vehicles waiting between the sensing zone of the approach vehicle detector and the stop line. Thus, minimum green is equal to either:
    - ☐ Initial portion of the green interval
    - ☐ Initial portion of the interval plus one extension interval
    - ☐ WALK interval plus pedestrian clearance, or

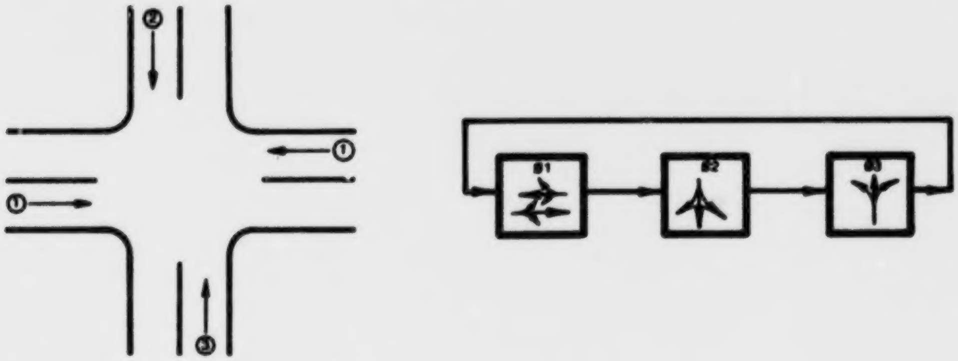


Figure 6.3. Phase sequence for single-ring controller

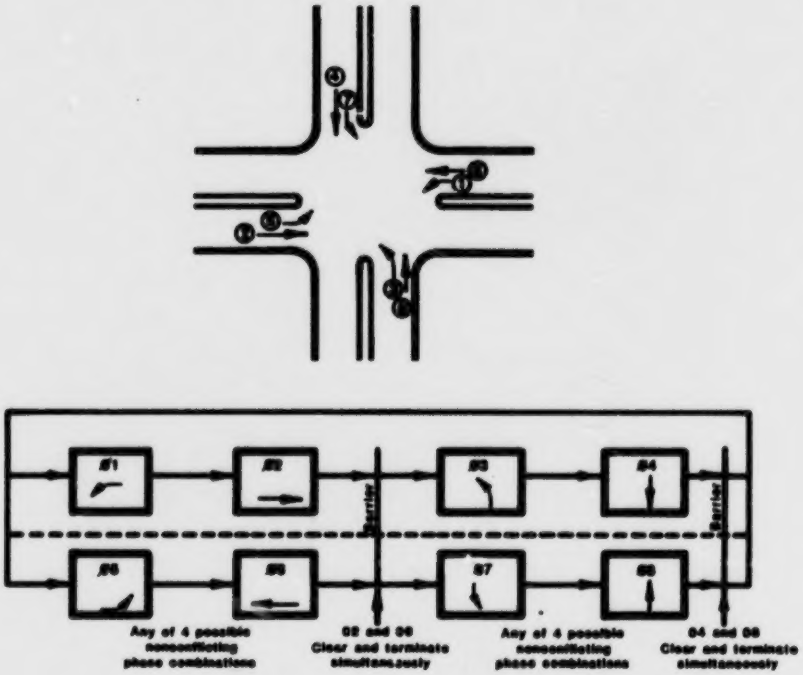

Ø1
Ø2
Ø3
Ø4
Ø5
Ø6
Ø7
Ø8
Barrier
Barrier
Any of 4 possible nonconflicting phase combinations
Ø2 and Ø6 Clear and terminate simultaneously
Any of 4 possible nonconflicting phase combinations
Ø4 and Ø8 Clear and terminate simultaneously

Figure 6.4. Phase sequence for dual-ring controller

  - WALK interval plus pedestrian clearance plus one extension interval (*4*).

- Extension (gap) interval — The portion of the green interval, the timing of which is reset with each subsequent vehicle actuation, and does not commence to time again until the vehicle actuation signal is removed from the input to the controller unit. This extensible portion of the green interval is subject to termination by the maximum or extension limit time function (*4*).

- Maximum (extension limit) — A time setting which determines the length of time that the respective phase may be held in green in the presence of an opposing serviceable call. In the absence of a serviceable conflicting call, the maximum timer is held reset (*4*). This maximum (extension limit) can be modified by selection of preset, alternate green interval extension limits (MAX I, MAX II, etc.).

- Yellow change interval — The interval following green which alerts motorists to imminent phase termination.

- Pedestrian (WALK) interval — The interval used to initiate the assignment of pedestrian crossing time. The setting is actually a guaranteed minimum and fixed time for the display of WALK.

- Pedestrian clearance (DONT WALK) interval — The interval following the pedestrian WALK indication which provides time for the pedestrian(s) to leave the curb and travel to the center of the furthest traveled vehicle lane before opposing vehicles receive a green indication.

- Red clearance interval — An interval which, when selected, follows the yellow change interval, and during which both the terminating phase and the next (conflicting) phase display red.

These settings are all implemented (per phase) on state-of-the-art full-actuated controller units via front-panel entry.

Special Operational Features. In dual-ring operation, full-actuated controller units are capable of a number of different phasing sequences between barriers (compatibility lines). There are three basic phase sequences for each of the two major phase groups. The following descriptions of each of the phase sequence options, as shown in Figure 6.5, assume that demand is present to initiate each phase:

- Left turns first — The sequence begins with Phase 1 and Phase 5, the opposing turns moving together. As demand ends or maximum green is reached on either Phase 1 or Phase 5, the respective left turn is terminated after the proper change and clearance intervals, and the opposing through movement (Phase 2 or Phase 6) is given a green indication concurrent with its accompanying left turn. As demand ends or maximum green is reached on the remaining left turn movement, it is terminated after the proper change and clearance intervals, and its opposing through movement is released. Phases 2 and 6 then run together until demand ends or maximum green time for both phases is reached. The phases then, after display of proper change and clearance intervals, terminate simultaneously at the barrier line. As shown in Figure 6.5, the above phase sequence also applies to the

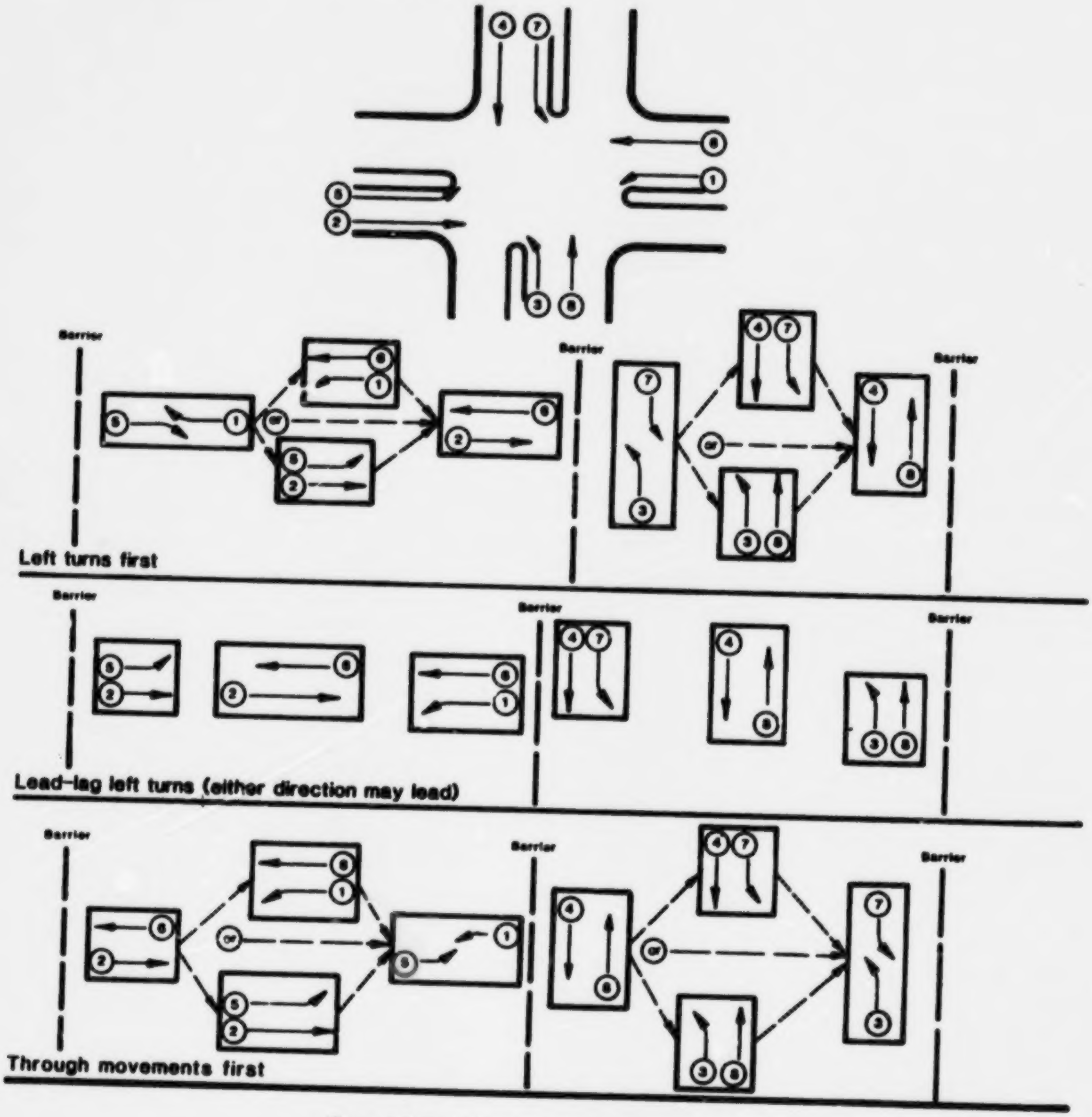


Figure 6.5. Dual-ring basic phase sequence options

phases beyond the barrier line (Phases 3, 4, 7 and 8), in the other phase group.

- Lead-lag left turns — The sequence begins with Phase 5, a left turn, and its accompanying Phase 2, moving concurrently. As demand ends or maximum green is reached on Phase 5, that left turn is terminated after the proper change and clearance intervals. The opposing through movement, Phase 6, is released to run with Phase 2. As demand ends or maximum green for Phase 2 is reached, it is terminated after the proper change and clearance intervals. Its opposing left turn, Phase 1, is released to run with accompanying through movement, Phase 6. When demand ends or maximum green is reached on Phase 1, both phases terminate, after the proper change and clearance intervals, at the barrier line. As shown in Figure 6.5, the above phase sequence also applies to the phases beyond the barrier line (Phases 3, 4, 7, and 8), in the other phase group. Also, it must be noted that either of the opposing left turns in each phase group may lead the phase sequence.

- Through movements first — The sequence begins with the opposing through movements, Phases 2 and 6. As demand ends or maximum green is reached on one of the through movements, that phase (2 or 6) is terminated after the proper change and clearance intervals, and its opposing left turn (Phase 1 or 5) is released to run concurrently with the accompanying through movement. As demand ends or maximum green is reached on the through movement, that phase (2 or 6) is terminated after the proper change and clearance intervals, and its opposing left turn (1 or 5) is released. Both left turns run together until demand ends or maximum green on the latest released phase is reached. Phases 1 and 5 then terminate simultaneously after the proper change and clearance intervals at the barrier line. As shown in Figure 6.5, the above phase sequence also applies to the phases beyond the barrier line (Phases 3, 4, 7 and 8), in the other phase group.

In Figure 6.5, identical phase sequences are shown for each phase group in respective phase sequence options. In practice, a given sequence, such as left turns first, could be applied to one phase group (Phases 1, 2, 5, and 6), and a different sequence, such as lead-lag left turns, applied to the other phase group (Phases 3, 4, 7 and 8).

NEMA-type controller units are capable of the above described sequences through internal or external manipulation. Sequencing thus can be selected by the user through software, "black box," or manually hardwiring of the controller unit.

The external control functions (inputs) which characterize NEMA traffic signal controller units and the manner in which they operate are discussed below. They are grouped into three categories: inputs per phase, inputs per ring, and inputs per controller unit.

The functions and manner of operations relevant to inputs per phase include the following:

- Vehicle Detector Call is a provision to enter a vehicle demand for service into the appropriate phase of the controller unit.
- Pedestrian Detector Call is a provision to enter a pedestrian demand for service into the associated phase of the controller unit.
- Hold is a command that retains the existing right-of-way and has different responses, as follows depending upon operation in the vehicle nonactuated or actuated mode:
  - ☐ For a nonactuated phase, energization of the hold input maintains the controller unit in the timed-out walk period with green and walk indications displayed. Energization of the hold input while timing the WALK portion of the green interval does not inhibit the timing of this period. De-energization of the hold input and with the WALK interval timed out causes the controller unit to advance into the pedestrian clearance interval. Re-application of the hold input while timing the pedestrian clearance portion of the green interval neither inhibits the timing of this period nor the termination of the phase.
  - ☐ For an actuated phase, energization and de-energization of the hold input is as follows:

a. Energization of the hold input allows the controller unit to time normally but inhibits its advance into the yellow change interval. Energization of the hold input inhibits the recycle of the pedestrian service unless the pedestrian recycle input is active and a serviceable pedestrian call exists on the phase. The rest state signal indications for that phase are green and DONT WALK.

b. De-energization of the hold input allows the controller unit to advance into the green dwell/select state when all green periods are timed out.

c. De-energization of the hold input with all intervals timed out allows the controller unit to recycle the walk interval if there is no conflicting demand for service and a pedestrian call exists for that phase. However, if there is any serviceable demand on an opposing phase with the hold input de-energized, and with all intervals timed out, the controller unit advances into the yellow change interval and does not recycle the walk on that phase until those demands have been served.

- Phase Omit is an input command which causes omission of a phase, even in the presence of demand, by the application of an external signal, thus affecting phase selection. The omission continues until the signal is removed. The phase to be omitted does not submit a conflicting call to any other phase, but accepts and stores calls. The activation of Phase Omit does not affect a phase in the process of timing.
- Pedestrian Omit is an input command which inhibits the selection of a phase resulting from a pedestrian call on the subject phase, and it prohibits the servicing of that pedestrian call. When active, the Pedestrian Omit prevents the starting of the pedestrian movement of the subject phase. After the beginning of the subject phase green, a pedestrian call is serviced or recycled only in the absence of a serviceable conflicting call and with Pedestrian Omit on the phase nonactive. Activation of this input does not affect a pedestrian movement in the process of timing.

The functions and manner of operations relevant to inputs per ring include the following:

- Force Off is an input command which provides for the terminations of green timing or WALK hold in the nonactuated mode of the active phase in the timing ring. Such termination is subject to the presence of a serviceable conflicting call. The Force Off is not effective during the timing of Initial, WALK or pedestrian clearance. Force Off is effective only as long as the input is sustained.
- Red Rest is an input which requires the controller unit to rest in red in all phases of the timing ring(s) by continuous application of an external signal. The registration of a serviceable conflicting call results in the immediate advance from Red Rest to green of the demanding phase. The registration of a serviceable conflicting call before entry into the Red Rest state, even with this signal applied, results in the termination of the active phase and the selection of the next phase in the normal manner, with appropriate change and clearance intervals. The registration of a serviceable call on the active phase before entry into the Red Rest state even with this signal applied, results (if Red Revert is active) in the continuation of the termination of the active phase with appropriate yellow change interval and Red display for the duration selected in Red Revert. The formerly active phase is then reassigned right-of-way.
- Inhibit Maximum Termination is an input which disables the maximum termination functions of all phases in the selected timing ring. This input does not, however, inhibit the timing of Maximum Green.
- Omit Red Clearance is an input which causes the omission of Red Clearance timing intervals.
- Pedestrian Recycle is an input command which controls the recycling of the pedestrian movement. The operation is dependent upon whether the phase is operating in the actuated or nonactuated mode:
  - ☐ In the actuated mode, if a serviceable pedestrian call exists on the subject phase and the Hold input is active, the pedestrian movement is recycled when the Pedestrian Recycle input is active, regardless of whether a serviceable conflicting call exists.
  - ☐ In the nonactuated mode, if the subject phase has reached the Green Dwell/Select state, the Pedestrian Omit is not active on the phase and a serviceable conflicting call does not exist, the pedestrian movement is recycled when the Pedestrian Recycle input is active.
- Stop Timing is an input command which, when activated, causes cessation of controller unit ring timing for the duration of such activation. Upon the removal of activation from this input, all portions which are timing, will resume timing. During Stop Timing, vehicle actuations on non-Green phases are recognized; vehicle actuations on Green phase(s) reset the Passage Time timer in the normal manner; and the controller unit does not terminate any interval or interval portion or select another phase, except by activation of the Interval Advance input. The operation of the Interval Advance with Stop Timing activated clears any stored calls on a phase when the controller unit is advanced through the green interval of that phase.
- Maximum II (selection) is an input which allows the selection of an alternate maximum time setting on all phases of the timing ring.

The functions and manner of operation relevant to inputs per controller unit are the following:

- AC + (Line Side) is the fused side of the 120-v AC, 60-Hz power source to the controller unit.
- AC − (Common) is the unfused and unswitched side of the 120-v AC, 60-Hz power source taken from neutral output of the AC power source. This input is not connected to Logic Ground or Chassis Ground within the controller unit.
- Chassis Ground is an input terminal for connection to the chassis of the unit. Chassis Ground is electrically connected to the shell of the connectors, but it is

not connected to Logic Ground or AC - (Common) within the controller unit.

- Interval Advance is a complete On-Off operation of this input which causes immediate termination of the interval in process of timing. When concurrent interval timing exists, use of this input causes immediate termination of the interval which would terminate next without such actuation. (A number of conditional situations regarding use of input and the resulting events are listed in Section 14 of the NEMA Standards (*4*), and reference should be made to that publication for further information concerning the Interval Advance Command).
- Manual Control Enable is an input which places vehicle and pedestrian calls on all phases, stops controller unit timing in all intervals, and inhibits the operation of the Interval Advance input during vehicle change and clearance intervals. (For several conditional situations regarding the use of this input in conjunction with Interval Advance, refer to those listed in Section 14 of the NEMA Standards (*4*).)
- Call to Nonactuated Mode (2 per controller unit) is an input provided, which, when activated, causes any phases appropriately programmed to operate in the nonactuated mode. The 2 inputs are designated Call to Nonactuated Mode I and Call to Nonactuated Mode II, respectively. (See Section 14 of the NEMA Standards (*4*) for detailed information on the 4 states of the Call to Nonactuated mode operation.) Only phases equipped for pedestrian service are to be used in a nonactuated mode operation.
- External Minimum Recall to All Vehicle Phases is an input which places recurring demand on all vehicle phases for a minimum vehicle service.
- External Start is an input which causes the controller unit to revert to its programmed initialization phase(s) and interval(s) upon application of the signal. Upon removal of this input, the controller unit commences normal timing.
- Walk Rest Modifier is an input which, when activated, modifies nonactuated operation only. Upon activation, the nonactuated phase(s) remain in the timed-out WALK state (rest in WALK) in the absence of a serviceable conflicting call without regard to the Hold input status. With the input nonactive, nonactuated phase(s) do not remain in the timed-out WALK state unless the Hold input is active. The controller unit recycles the pedestrian movement when reaching the Green Dwell/Select state in the absence of a serviceable conflicting call.

Hardware Characteristics

Environmental and Operating Requirements. Environmental and operational requirements and procedures for conformance testing for control equipment are referenced as follows:

- For the Model 170 control equipment, see Hardware Specifications, Federal Highway Administration, IP-78-16, December 1978 (*5*).
- For NEMA control equipment, see Traffic Control System Standards, Publication No. TS1-1983, National Electrical Manufacturers Association (*4*).

The hardware specifications for the Model 170 control equipment list general environmental and operational requirements and test procedures in Section VIII of Chapter 1 of the Specifications (*5*). Additionally, each of the subsequent chapters of the specification, which are oriented to specific system components, contain sections which address functional, electrical, and mechanical requirements for the respective components.

The traffic control systems standards for NEMA control equipment list the general environmental standards and test procedures for all the system components in Section 2 of the Standards (*4*). Additionally, Sections 5 through 11, which are oriented to specific system components, address electrical requirements for respective components of the traffic control system.

Conflict and Voltage Monitor. By detecting the presence or absence of voltages at field terminals, the conflict monitor detects conflicting signal indications. These functions replace the mechanical display interlock inherent in the old-style electromechanical units. The monitor also assures the presence of satisfactory operating voltages within the controller unit and within itself. Upon the detection of conflicting indications or an unsatisfactory operating voltage, the monitor will cause immediate transfer of the signal operation to a preprogrammed flashing condition.

(See Section 6 of the NEMA Standards (*4*), and Chapter 3 of the Model 170 Specifications (*5*) for information on conflict and voltage monitors for the respective controller units.)

External Logic Devices and Software Logic (Special Logic). In the past, many controller-related logic functions took place within external logic devices, proverbially known as "black boxes." Coordination units, preemption logic, lead-lag phase selection and time-based coordination are examples of functions which were carried out by external logic devices. Although these and other functions are considered add-on controller unit features and are still manufactured separately today, most controller manufacturers (or users) now incorporate the features via integral software. Therefore, although this special function logic may carry the name "external logic," it no longer really applies in the physical sense.

Special external logic devices or internal software may be used for special phasing applications. Generally speaking, the standard phasing of an 8-phase, full-actuated controller is converted into very unique phase sequencing for special applications which the standard phasing cannot satisfy. Two examples of special phase sequencing are as follows:

- The operation of a standard 8-phase controller unit in such a manner that, on one or more approaches, the service of a left turn can be restored without first cycling through the barrier line. In this operation, commonly known as conditional service, the controller unit monitors the time remaining on any through movement phase which is opposed by a through phase which has gapped out. If the time remaining on the nongapped phase is sufficient for at least a minimum service of its associated (parallel) left-turn phase, the controller unit terminates the gapped-out phase and reservices the left-turn. Figure 6.6 illustrates the phase sequence.

  The operation of an 8-controller unit in a protected-permissive state for left turns negates any need for conditional service phase sequencing.

- The operation of a standard 8-phase controller unit for special phasing for signalization of a full-diamond interchange. Two sequence variations are shown in Figure 6.7 as described below:

  - ☐ A 3-phase, lag-lag operation in which the traffic on both ramp approaches is released simultaneously (Phase 1). Subsequent vehicle actuations and/or maximum green time-outs determine diagram flow from Phase 1 to one of the four overlap phases, or directly to Phase 2. Depending upon demand registered and which Phase 1 overlap was previously served, the controller unit will move to serve one of the two Phase 2 overlaps or go directly to Phase 3. In the absence of demand from either ramp approach, the controller unit may proceed from Phase 3 back to Phase 2, or to one of the two Phase 2 overlaps.

  - ☐ A 4-phase operation with two overlaps, in which traffic on one of the ramp approaches is released simultaneously with through and left turn traffic (on the intersecting arterial) at the other ramp intersection, thereby clearing any possible internal queue for the traffic turning left from the ramp (Phase 1). As shown in the diagram in Figure 6.7, several optional flow paths are available, any of which could be followed, based upon registered

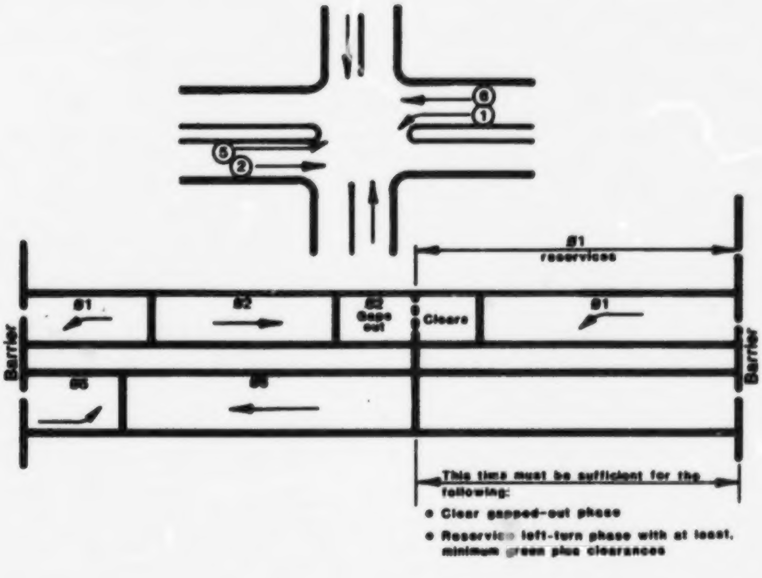
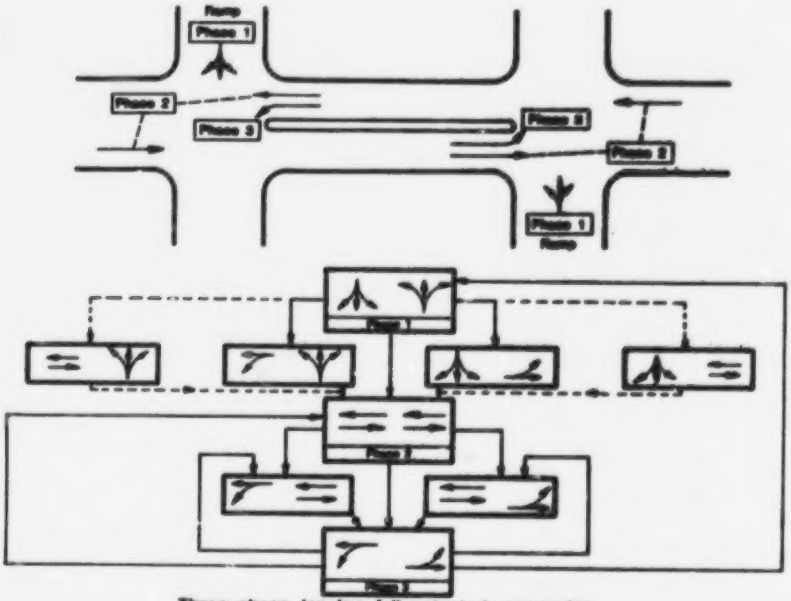
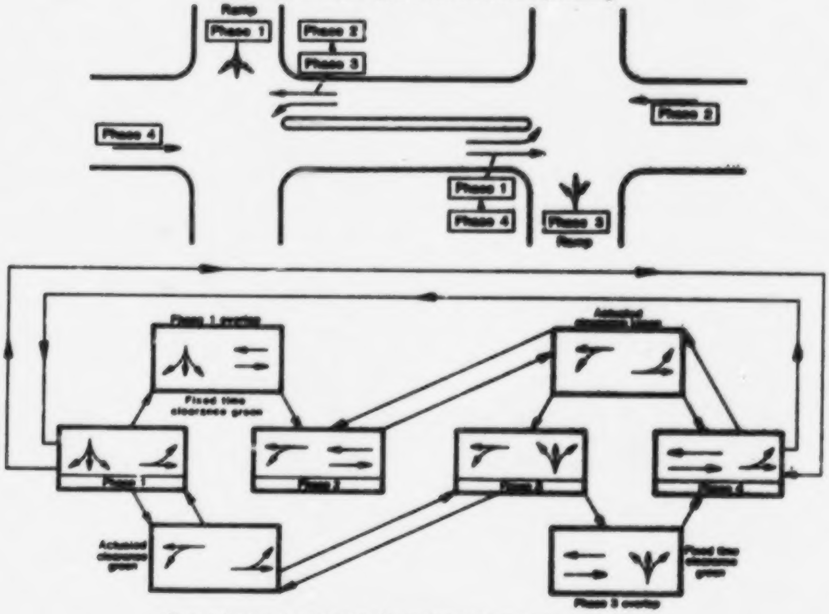

⑥
①
⑤
②
Ø1
reservices
Ø1
Ø2
Ø2
Gaps
out
Clears
Ø1
Barrier
Ø5
Ø6
Barrier
This time must be sufficient for the following:
• Clear gapped-out phase
• Reservice left-turn phase with at least, minimum green plus clearances

Figure 6.6. Example of special phase sequence for conditional service of left-turn phase


Ramp
Phase 1
Phase 2
Phase 3
Phase 3
Phase 2
Phase 1
Ramp
Phase 1
Phase 2
Phase 3

Three-phase, lag-lag, full-actuated sequencing


Ramp
Phase 1
Phase 2
Phase 3
Phase 2
Phase 4
Phase 1
Phase 4
Phase 3
Ramp
Phase 1 overlap
Actuated clearance green
Fixed time clearance green
Phase 1
Phase 2
Phase 3
Phase 4
Actuated clearance green
Fixed time clearance green
Phase 3 overlap

Four-phase sequencing (principal phases are actuated)

Figure 6.7. Special diamond interchange phasing

Source: Reference (*13*)

demand and/or maximum green time-outs on certain approaches. For purposes of illustration, the following flow sequence assumes continuing demand on all detectors.

From Phase 1, the controller unit moves to Phase 1 overlap, in which the opposing traffic on the arterial (at the, as yet, unserved ramp intersection) is released while the ramp approach green continues. The Phase 1 overlap phase must be of fixed time duration since the running ramp green must be terminated to accommodate the progressive movement of the arterial traffic released at the start of the overlap phase. This fixed time period is determined by the travel time of accelerating arterial traffic from a stop at one ramp intersection, and through the other ramp intersection.

The controller unit proceeds then to Phase 2 green to accommodate the above described approaching arterial traffic (through and left turns). For Phase 3 initiation, traffic on the arterial (at the, as yet, unserved ramp) is cleared and terminated for released of traffic on the ramp approach. As the diagram shows, flow continues to Phase 3 overlap and on to Phase 4, serving remaining traffic movements. The rather complex array of flow lines and arrows on the diagram represents all possible sequence paths the controller may take. However, the sequence described above is the most likely path the controller unit would follow.

NEMA controller units, modified by internal software logic for the 3-phase and 4-phase sequences described, are presently in service in Texas (*13*). The operation can change between the two sequence options in response to external commands. Typical detector locations for operation of the controller unit in 3-phase, lag-lag, or 4-phase (with overlaps) sequencing, with locally produced external data, are shown in Figure 6.8. Software logic also provides the option for use of any compatible combination of phases at the ramp intersections, in response to computer-issued command data, as shown in Figure 6.9.

An interconnected signal system, consisting of six diamond interchanges under computer supervision, has been installed in Texas. When computer control is lost or intentionally discontinued, local interchange controller units maintain the (optional) 3-phase or 4-phase operation (Figure 6.7), based on local detector data (Figure 6.8) (*13*).

A Model 170 controller unit provided with the proper software is also capable of the above described operations. (The software package which is utilized and the resulting operation are described later in this chapter.)

System Capabilities

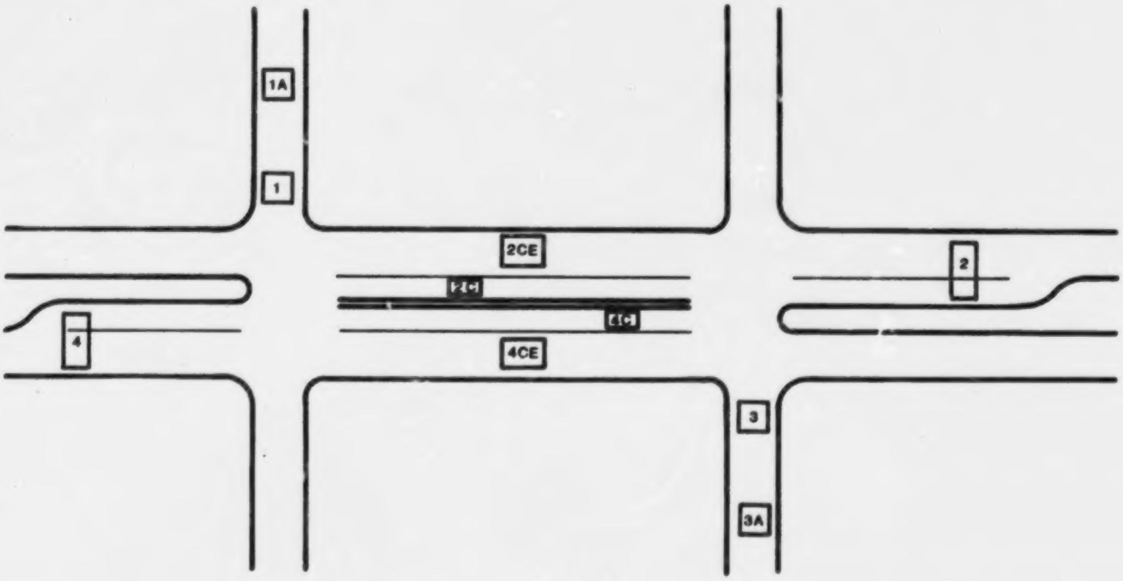
The full-actuated controller, when used as a local unit in a traffic signal system, is capable of additional functions outside of those previously described. Through the use of a communications module, which links the local controller unit to its supervising master or central computer, a variety of commands are received and implemented. In the more sophisticated network systems (usually computer supervised), a 2-way communications system returns information from the local unit to the central facility. The control status of the local controller and timing plan in effect are examples of local-oriented information which is returned. In many systems utilizing 2-way communications, system detector information is also returned to the supervising master unit or central computer.

Modified NEMA-type controller units and Model 170 units have the capability of altering the local phase sequencing in response to external commands for timing plan changes. In a 8-phase local controller unit, the deviations from the standard phasing (leading opposing turns), include lead-lag left-turn sequences and through movements first, as previously shown in Figure 6.5. The selection of certain of these phase sequence options can improve progression bandwidths in both arterial (open-system) and network (closed-system) street configurations.

Down-Loading Capabilities

The down-loading of signal timing plans is a feature available when microprocessor-based controller units are used as local controllers in a master or computer-supervised control system. Down-loading is a process in which the master unit or computer, via communications interface, can access and read the contents of the local controller unit random access memory (RAM) and alter any stored existing signal timing plan or load new plans. Access and/or manipulation is thus provided to phase sequencing, interval timing, number of intervals, offset points, and other timing plan characteristics. Individual intersection parameters stored in the RAM of the local controller unit(s) can also be manually accessed by the operator via the central facility, thereby overriding previous changes or commands. Down-loaded interval durations and phase sequences may be subject to local minimums or matrices stored in PROM or RAM locally, or the down-loaded data may overwrite existing data without restraint. Methods vary from system to system and traffic engineers must be aware of the resulting impacts on traffic flow and safe operations.

216



No.	Assoc. Phase	Functions for:		Detector No.	Assoc. Phase	Functions for:	
		30Lag, Lag	40W/Overlap			30 Lag, Lag	40W/Overlap
1	1	Phase detector	Phase detector	3	3	Phase detector	Phase detector
1A	1	(not used)	Phase detector during Ø1 when call is received for Ø2	3A	3	(not used)	Phase detector during Ø3 when call is received for Ø2
4	4	Phase detector	Phase detector	2	2	Phase detector	Phase detector
4C	4	Detector for left turn and interval clearance green	Switched on for calling only during Ø2 and Ø3 extending detector during clearance green	2C	2	Detector for left turn and interval clearance green	Switched on for calling only during Ø1 and Ø4 extending detector during clearance green
4CE	4	Extending detector	Switched on for calling only during Ø3 extending detector during clearance green	2CE	2	Extending detector	Switched on for calling only during Ø1 extending detector during clearance green

Figure 6.8. Typical detector configuration for 3-phase, lag-lag and 4-phase (with overlap) special sequences

Source: Reference (*13*)

6.8 MODEL 170 and NEMA CONTROLLERS

Model 170 Controllers

The Model 170 controller system is described in a specification (*5*) jointly developed by the states of California and New York. Although each state uses a slightly different variation of the specification, the conceptual approach of the Model 170 system is based on hardware standardization, and structures the controller assembly as a package consisting of standardized modules, complementary hardware and wiring harnesses, all housed within a standard cabinet enclosure. A typical front panel assembly for the Model 170 controller unit is shown in Figure 6.10. The controller unit uses a microcomputer which, with the addition of appropriate software, can be utilized in a variety of control applications. Thus, the controller unit can be tailored to the user's needs by incorporating an existing software program, by modifying an existing software program, or by developing a new program.

217

BEST COPY AVAILABLE

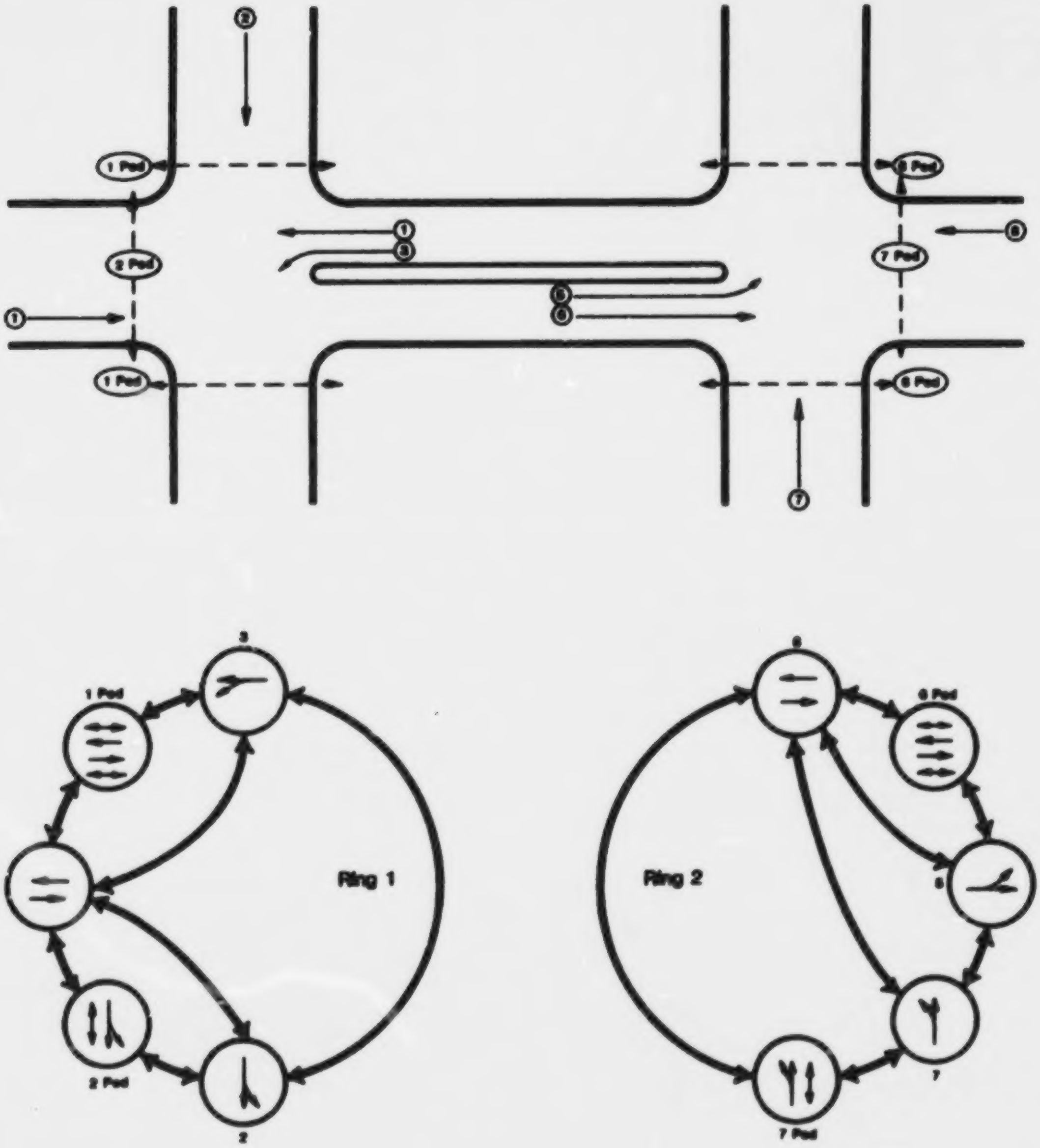

②
1 Ped
6 Ped
①
③
⑧
2 Ped
7 Ped
⑤
⑥
①
1 Ped
6 Ped
⑦
3
1 Ped
1
Ring 1
2 Ped
2
6
6 Ped
Ring 2
5
7
7 Ped

Figure 6.9 Computer-controlled diamond interchange operation

Source: Reference (*13*)

The development of new software or any substantial modification of standard programs requires considerable knowledge of the Model 170 software and the microprocessor used. Test and simulation equipment are used to verify the operation produced by the modified or new software program after the new program is "burned in" to the 170 PROM chip. Documentation of the new or modified program must then be produced and carefully checked for accuracy.

Software Programs. Software programs have been developed, successfully used, and are available for the Model 170 controller unit for use in the following control applications (*8*):

- Semiactuated and full-actuated control
- Pretimed (fixed time) control (multidial and multioffset)
- Ramp metering control
- Grid and arterial master control
- Diamond interchange control

For the software programs which are under development (not yet ready or available for general use) for the Model 170 controller unit, some of the applications are as follows:

- Hierarchical distributed multilevel traffic signal control
- Sprinkler control
- Traffic census and surveillance (*8*)

Model 170 controller units are in use at over 10,000 locations (1984) in the United States. Some utilize modified versions of nonproprietary software programs. A small percentage are equipped with unique software developed by the user or by other sources, such as engineering consultants.

Table 6.2 is a listing of traffic control software programs for the Model 170 and their current status. Not listed are software programs for various control applications which are available from several private software houses, or which may be supplied by manufacturers of the Model 170 as part of a bid package when specified by the user. The software, so acquired, may be a documented, public domain package or a modified version (*8*).

Local Intersection Program (LIP) — The Local Intersection Program (LIP) software was developed by the State of California Department of Transportation (Caltrans) for the accommodation of typical intersection control strategies. The program was designed for full-actuated, isolated operation, but its design allows it to be interfaced to a separate coordination program for use in interconnected traffic signal systems. LIP will perform the functions of a typical solid-state controller unit (2 through 8 phases). Four phases can have associated concurrent pedestrian movements, and all phases are capable of density timing. Each ring times concurrent with and independent of the other, and any phase without demand is skipped. The LIP program can be used for many applications of 2 through 4 phases, single-ring, and 5 through 8 phases, dual-ring. In addition to the above features, the program includes two programmable right-turn green-arrow overlaps, two railroad-preemption, and four emergency-vehicle-preemption sequences (*6*).

Isolated Traffic-Actuated Program (ITAP) — The Isolated Traffic Actuated Program (ITAP) software was developed by the State of New York Department of Transportation (NYDOT), and its traffic control philosophy closely parallels that of the LIP program. Two basic dual-ring operations are available in the ITAP program:

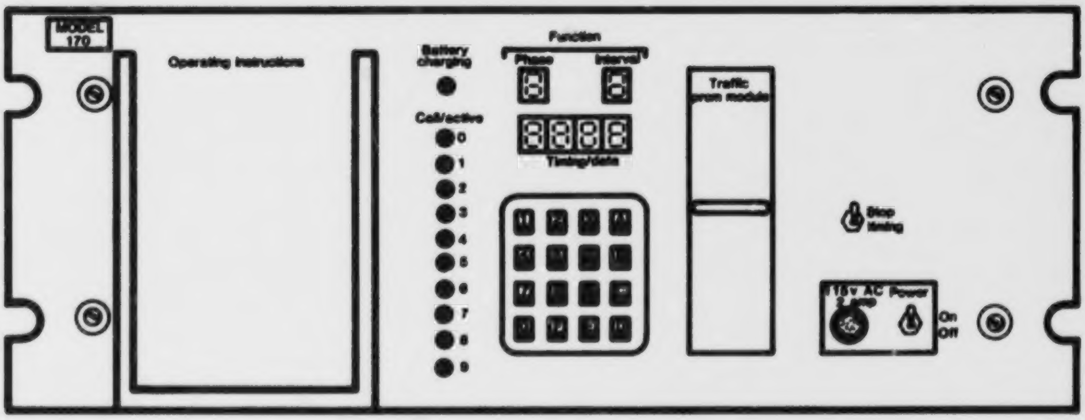


Figure 6.10. Model 170 typical front panel display

Source: Reference (*6*)

Table 6.2. Current status of selected Model 170 software programs

Program	Developer	Program Status
Local Intersection Program (LIP)	CA	Opnl
Isolated Traffic Actuated Program (ITAP)	NY	Opnl
Diamond Interchange Program (DIP)	CA, Cons	Opnl
Ramp Metering	CA	Opnl
Basic Arterial System (BASYS)	CA	Opnl
C3/C4 Master/Slave Progression	CA	Opnl
Acceptance Testing and Diagnostics Software (AT) and (STEP)	NY, CA	Opnl
UTCS Master/170 Local Interface	Cons	Opnl
Multisonics VMS-220 Master/170 Local Interface	Vendor	Opnl
Traffic Surveillance and Vehicle Classification	CA	Opnl
4-Phase Sequential Full-Actuated w/Parallel Pedestrian Movements	CA	Opnl
Yield (Mates Local 170 with Non-170 Via Yellow Yield)	CA	Opnl
(ET/EATS) Operation 1 170/NEMA	CA	Opnl
Master Traffic Actuated Program (MTAP)	NY	Under Test
Slave Traffic Actuated Program (STAP)	NY	Under Test
Eureka Distributed Multi-Level System (EDMS)	Cons	Under Test
Joint Agency AT and Diagnostics	NY, CA	Under Test
Econolite Master/170 Local	Vendor	Unknown
Time-Based Coordination	CA	Opnl

CA = Caltrans, California; NY = New York DOT; Cons = Consultant; Opnl = Operational

Source: Ref.rence (*8*)

- Standard dual-ring, quad-left operation with exclusive pedestrian WALK phase between the major phase groups.
- Dual-ring, 6-phase/sequential operation, with exclusive pedestrian WALK phase following the (1-2-5-6-half-ring) major phase group.

Both phase-rotation sequences are shown in Figure 6.11. Concurrent pedestrian movements (with associated phase) can be substituted via keyboard programming for the exclusive pedestrian WALK phase.

Unlike the LIP program, the 16 detector and preemption inputs used with the ITAP program must be assigned to specific functions via keyboard programming. Since the first eight input positions will accommodate time-delay options, they are suggested for use as vehicle detector inputs.

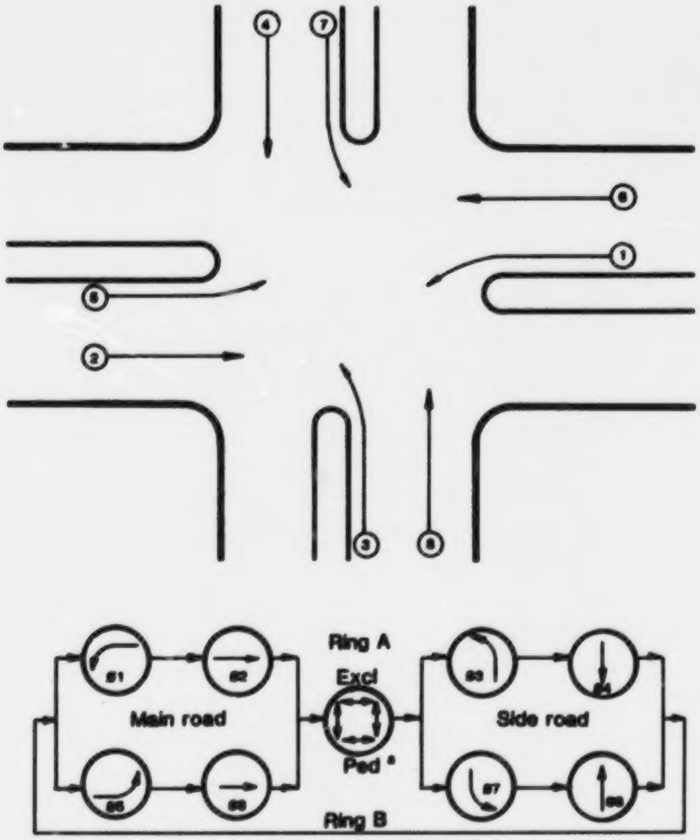
The ITAP program also includes provisions for programming right-turn green-arrow overlap phases, and railroad-preemption and emergency-vehicle-preemption sequences.

Diamond Interchange Program (DIP) — The Diamond Interchange Program software was developed by Caltrans to accommodate for signal control strategies for diamond interchanges, as follows:

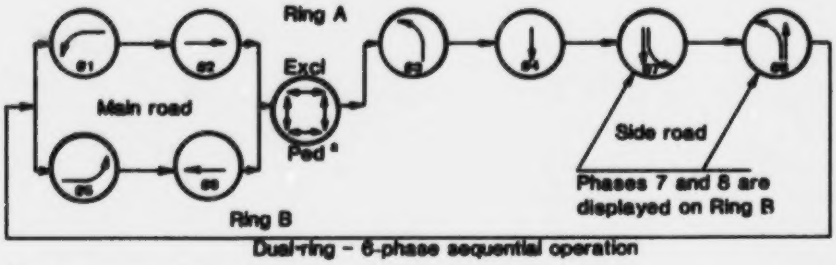
- A 3-phase, lag-lag sequence (as previously discussed in this chapter in the Full-Actuated Controllers section).
- A 4-phase sequence without overlaps (sequence can be implemented as full-actuated operation).
- A 4-phase, 2-overlap sequence (as previously discussed in this chapter in the Full-Actuated Controllers section, except that the operation is in fixed sequence, and it cannot be implemented in a traffic-actuated mode)
- The control of each ramp intersection of the interchange which functionally duplicates the operation by two, 2-ring controllers in one cabinet, as shown in Figure 6.12. Six phases have associated concurrent pedestrian movements, and there are capable of density timing. The 8 phases are arranged into 4 rings: 2 rings of 3 phases each, and 2 rings of 1 phase each. Each ring times concurrently with, and independent of, the other. Any phase without a demand is skipped when operated in the actuated mode (*7*).

The DIP is capable of selecting and implementing any of the above signal sequences by time-of-day, day-of-week,

220


4
7
6
1
5
2
3
8
Ring A
Excl
Main road
Side road
Ped a
Ring B
ø1
ø2
ø5
ø6
ø3
ø4
ø7
ø8

Quad left turn operation


Ring A
Excl
Main road
Ped a
ø1
ø2
ø5
ø6
ø3
ø4
ø7
ø8
Side road
Phases 7 and 8 are displayed on Ring B
Ring B

Dual-ring – 6-phase sequential operation

---

[a] Exclusive pedestrian phase may be omitted through keyboard programming.

Concurrent pedestrian timing (with associated through phase) may also be selected in lieu of exclusive phase.

Figure 6.11. Two basic phase operations for the ITAP program

or traffic-responsive selection. The traffic-responsive selection is based on pattern matching of selected detectors. An off-ramp queue-detection capability is also included in the software, and, if an excessive off-ramp queue is encountered, a special queue priority plan is implemented (*7*).

The coordination capability on a 7-wire system or via the internal modem which is included in the program is designed to allow the diamond interchange controller to serve as a master controller unit for adjacent intersections. The coordination software can accommodate 9 dials with 1 offset and 1 split per dial. The software is also adaptable for operation under control of a central master unit or other type master controller unit (*7*).

Basic Arterial System (BASYS) — A program for the Model 170 coordination, BASYS, was developed by Caltrans to operate and control a system of signalized intersections by time-base, telephone interconnect, or by one-pair or multiconductor direct-line AC interconnect (*9*).

BASYS software is comprised of two independent, but compatible, control programs titled as "Basic Arterial Master" (BAM) and "Basic Arterial Local Intersection" (BALI). The two programs, when resident and mated to both the Local Intersection Program (LIP) and required hardware, carry out their respective designed functions of control and coordination. Certain LIP modifications are required to provide coordination interface and program enhancements when the BASYS programs (BAM and BALI) are implemented (*9*).

The BAM and BALI programs are structured to operate either remote from each other (in separate controller units) or on the same traffic PROM module. Common PROM installation of the two programs provides time-base control of the local controller unit in a primary or backup mode (*9*).

The Basic Arterial Master (BAM) program when placed in a Model 170 controller unit in the traffic PROM module will interface with the Basic Arterial Level Intersection (BALI) programs resident in other (local) Model 170 controller units, and it will supervise a traffic signal coordinated progression system via telephone wire pairs (modem) and/or standard 7-wire-type AC direct-line interconnect (*9*).

The Basic Arterial Local Intersection (BALI) program, when placed in a Model 170 controller unit in the traffic PROM module will interface with and supervise its Local Intersection Program (LIP). BALI, when activated, reads in-house or remote (BAM) master by scanning mode of communications (operator-selected type), and by the implementing proper master commands.

For more detailed information on the Basic Arterial Master System (BASYS), see Chapter 7 of the Handbook.

NEMA Controllers

Some electrical equipment manufacturers have voluntarily agreed to conform to the traffic signal controller units they manufacturer to NEMA Standards Publication No. TSI-1983 (*4*). These standards reflect inputs from traffic engineers, installers of traffic signal equipment, and professionals in the field of traffic control, and describe physical and functional requirements for full-actuated traffic signal controller units and ancillary equipment. The controller unit functions described in the standards include 2-phase through 8-phase, single-ring and dual-ring operation. Input and output formats, environmental standards, and test procedures are also covered in the standards, which were developed to provide compatibility and interchangeability in controller units.

Although manufacturers of NEMA controller units must produce equipment which functionally satisfies the standards, many state-of-the-art units have additional operational features. Some special operations which NEMA controller units perform were covered earlier in this chapter.

Comparison of NEMA and Model 170 Controllers

The concepts of the NEMA and Model 170 controllers are quite different. NEMA controller units are designed and manufactured in various electronic arrays, but all must conform functionally to the NEMA Standards. Certain physical requirements for auxiliary and ancillary equipment must also be met to maintain compatibility between certain components. Model 170 controller units, on the other hand, are microprocessors conforming to the Model 170 Hardware Specification which describes the physical performance and mechanical requirements of the unit. As manufactured, the Model 170 unit is not capable of performance as a traffic signal controller. The user must provide (or procure from other sources) a software program and install it in the traffic PROM module of the unit. This program provides the brain necessary for the microprocessor to perform as a signal controller unit. The program may be a documented non-proprietary type or, a modification of some documented program, or it may be an original, perhaps devised for use of the Model 170 in an application other than traditional traffic signal control.

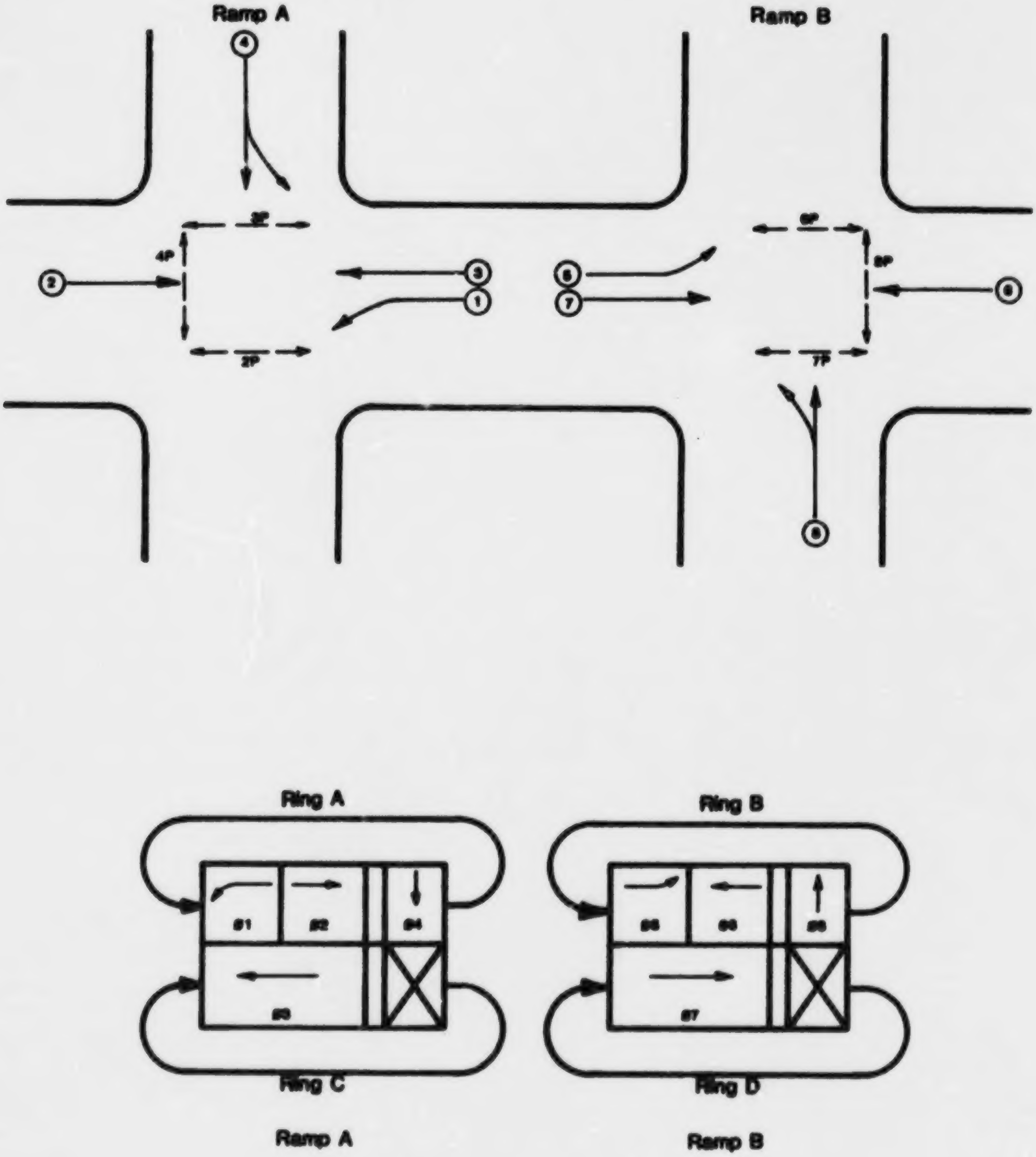

Ramp A
Ramp B
4
4P
2
3
1
5
7
8P
6
7P
8
Ring A
Ring B
#1
#2
#4
#3
#5
#6
#8
#7
Ring C
Ring D
Ramp A
Ramp B

Figure 6.12. Phase sequence option in DIP software

Source: Reference (7)

Although changeable software programs are not employed, many manufacturers of NEMA units use the microprocessor concept, satisfy the NEMA functional requirements, and also provide a means for programming special additional functions by the user.

Table 6.3 lists some items for a comparison of likeness/differences in the Model 170 and NEMA controller concepts.

Potential users should realize that each approach has its own variety of qualities, range of applicability, procurement ramifications, staffing requirements for maintenance, spare equipment requirements, and overall costs which must be studied prior to use in a particular location or by a specific entity. Prospective users should give careful consideration to both approach concepts, and should recognize that standardization, however conceived or applied, is a means to the end of achieving safe, effective, and energy-efficient traffic control.

6.9 LOCAL CONTROLLER COORDINATION

Function

The coordination of local controllers in a signal system can be accomplished by using one of the following two basic concepts:

- Supervision of the local units by a master controller. Interconnection of the master and locals is required, either by physical means or by the use of radio or other air-path communication media.
- Supervision of each local controller by an internal device, which has the capability of retaining a very accurate time relationship with like devices which are supervising other local units in the system.

Table 6.3. Items for comparison of NEMA and Model 170 controller units

Basis for Comparison	NEMA	Model 170
Design	Usually microprocessor-based, but must functionally conform to NEMA Standards of operation for traffic signal controller	Microprocessor-based, but functions are a result of the specific software program installed in PROM module
Standards/ specifications	Not hardware specific a. Define functional, environmental, physical and interface b. Objectives — Attain compatibility and interchangeability of equipment c. Provide for standard operation and performance as traffic signal controller	Hardware-oriented a. Define environmental, physical, self diagnostics, and interface b. Objectives — Interchangeability, minimized costs for procurement, simplified maintenance c. User and/or vendor are responsible for operation and software program used
User access	Usually via keyboard — some units employ thumbwheels, DIP switches, or program pins	Via keyboard — Some units employ hexadecimal system for programming-coding
Software	Tested and supplied by vendor	Vendor or user (or other source) may supply
Adaptation for special use	Difficult, since Standards define functions and PROM is "fixed" by vendor to carry out tailored program per NEMA	Standards do not cover functions; specific PROM can be installed to that virtually any mode or application can be carried out
Maintenance and trouble shooting	Microprocessor-based in most controller units, but oriented to function by phase, sequence, or interval	Oriented to microprocessor addressor data base; requires more advanced electronics knowledge
I/O interface	Inputs and outputs are function — specific by pin assignment	Software used directly assigns inputs and outputs, by pin, on some models. Others have feature which reassigns individual I/O pins from keyboard by user
Cabinets	Not standardized in size or component placement within, from one manufacturer's product to another	Standard-size wiring layout and component placement within cabinet specified for uniformity

Source: Reference (*6*)

224

Forms of Interconnection

As previously stated, interconnection media between master and local controllers can take one of the following two forms (physical or air-path communication):

Physical. The physical type of interconnection is usually installed in underground conduit or tile duct, although the method of linking master and locals could be via direct-burial cable or pole-mounted overhead runs. Some of the physical type interconnect media include the following:

- A multiconductor, cable interconnect which usually operates on 110-v AC, with one conductor per master/local function. This type is used extensively for electromechanical local and master controller systems.
- A telephone-type small-gauge wire pair interconnect which operates in a low-voltage range. The wire pairs used may be leased or agency owned. In this concept, each system link runs from modem to modem (modulation/demodulation units), which are located in controller cabinets in the system. Two common wire pairs usually link the master unit to several local controllers. With this arrangement some method of signaling must be used on the wire pairs so that messages for individual locals can be recognized.
- A coaxial cable, small-gauge conductor surrounded by foam and shielded, which is used for transmission of high-frequency signals. It requires the use of modems, as described above. A coaxial cable, when used in signal systems may be agency owned and dedicated. The shared-use of cable television coax for signal system communication links has also been successful in some cities.
- Fiber-optic cable, small optic fibers of plastic material, sheath-encased, through which digitally coded, high-intensity light is transmitted. Digital encoder/decoder devices are required, and any very long distance transmission requires repeater/ booster terminals.

(See Chapter 8 for a more extensive discussion of these and other types of physical communication and interconnection.)

Air-Path Communication. This type of interconnection relies upon transmission and reception of signals via radio or other air-path phenomena. Required in this system are transmitter and receiver units for each desired direction of data flow.

Some air-path type interconnect media include the following:

- Radio communications, usually FM and requiring general "line-of-sight" location of transmitters/receivers for reliable operation. This concept has been used in the past in a few installations, but because of expensive parts, unreliability, and the difficulty of maintenance, no recent installations have taken place.
- Microwave is a communication method commonly used in the transmission of video information. Because of its high capacity for transmitted information, it is readily adaptable as an interconnection medium, especially where long distance air-paths are necessary. As with FM radio, a line-of-sight between transmitter and receiver is necessary. The required FCC separation and assignment of frequencies may present problems to potential users.
- Laser is a relatively new concept for air-path interconnection. This medium transmits and receives coded digital information at a very high rate via the opening and closure of a very narrow laser beam. As in the other air-path concepts, line-of-sight between units is mandatory. Because the narrow band laser beam must be limited in intensity to protect the public, the performance of the system over long distances in fog, rain, or similar atmospheric phenomena is marginal.

(See Chapter 8 for a more in-depth discussion of air-path type communications and interconnection.)

Time-Base Coordination

In this form of signal system coordination, each local controller is supervised by a very accurate time-base device. Cycle pulse reference, dial or timing plan changes, and other commands which normally flow from a master-driven coordination unit are produced by a unit located in the cabinet or by specific software in the controller unit. The time-base coordinator is equipped with a rechargeable battery capable of about 30-day usage, and which, in case of local power failure, retains memory and clock time, for resumption of correct operation when power is restored. In normal operation these devices derive their clock accuracy from the 60 Hz alternating power line current. The time-base coordinator may be a separate piece of hardware or may be integral to the controller unit (as in the Model 170 and many NEMA controller units). (See Chapter 7 for a more detailed discussion.)

225

6.10 FACTORS IN CONTROLLER SELECTION

The selection of the proper type of control can be a difficult and time-consuming process. In 1981, the National Cooperative Highway Research Program (NCHRP) published Report 233 which contains information to aid the traffic engineer in an evaluation of the various control alternatives. Included in the report is information needed to select the most appropriate type of signal equipment for an individual intersection in urban or rural areas. In this text, emphasis is placed on traffic control at isolated intersections. Adjacent intersections are considered insofar as the identification of the need for coordinated operation is concerned (*2*).

Controller selection should ultimately be based on the computed benefits and costs which are a function of the following: roadway characteristics, traffic characteristics, and control characteristics. The relationship of these elements as applied to controller selection is shown in Figure 6.13. The final selection of type of control is based on comparison of costs and benefits of alternative control techniques (*2*).

Benefits to be used for comparison should include safety, traffic flow, fuel comsumption, and vehicle emissions. Traffic flow variables are stops and delays associated with the individual intersection.

The costs used in the procedures are those associated with the design, installation, operation and maintenance of the basic controller equipment. The costs include equipment and labor, and, in the case of actuated equipment, the detectors. Signal displays, cabinets, and other equipment common to all forms of control are not included in the costs (*2*).

In the following text, only the control aspect of the selection process is discussed. See NRCHP Report 233 (*2*) for an in-depth study of roadway and traffic characteristics.

Operating Requirements and Constraints

Any review of control options must flow from a consideration of the specific needs at the intersection, with modifications to reflect policy considerations. The review should answer the question, "What are the operating characteristics of the intersection?" An analysis of existing geometry, approach demand, turning movements, accident profiles, approach speed, delays, expected future conditions and other factors will define the intersection operating requirements.

Along with the operating requirements, operation constraints must be identified. It is recognized that improving traffic signal performance will not cure all problems. If demand consistently exceeds capacity, the best controller and detection system will not alleviate congestion. Good hardware will not improve bad operation if the signal timing is poor, and a well-timed actuated controller becomes a poor pretimed controller when detectors become inoperative (*2*).

An analysis of the intersection operating characteristics and requirements will yield information on the appropriate type of control, the proper phasing, and a good indication of what the cycle length(s) and associated interval timings should be. Various phasing options will likely

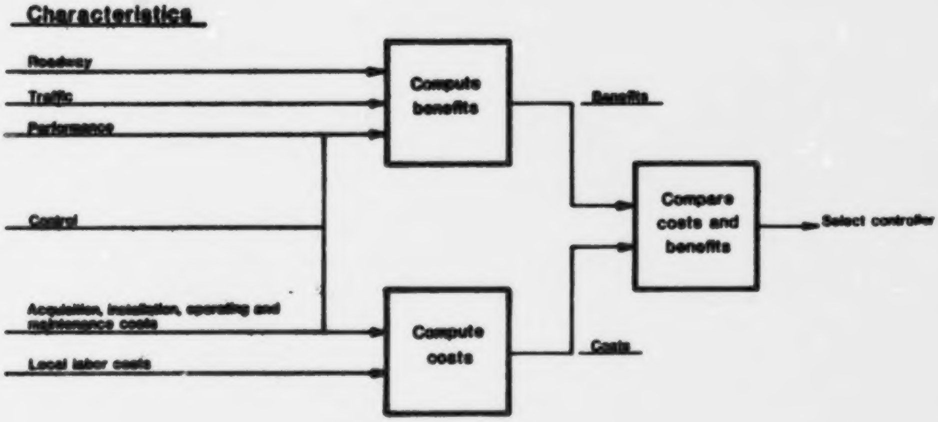


Figure 6.13. Controller selection process

Source: Reference (*6*)

come to light, especially if left-turn phasing is required. All options should be thoroughly investigated and analyzed for the effect of each on intersection capacity and for accident potential (*2*).

A tool for developing signal control plans at isolated intersections is available to the traffic engineer. The Signal Operations Analysis Package (SOAP) is computer software through which a wide range of control alternatives can be evaluated, including pretimed and actuated with multiphase control plans. SOAP determines the optimal signal timing and phasing, and produces several measures of effectiveness (MOE'S) including delay, stops, fuel consumption, V/C ratio, and left turn conflicts. Phasing diagrams are also included. SOAP (which was developed by Kenneth G. Courage, Tetsuo Yoshidan, and Mark R. Landmann of the University of Florida Transportation Research Center; and Gary Price of the Florida DOT) is available from the FHWA (HRT-20), Washington, D.C.

Anticipated Effects and Costs

It is important to identify the effects that are anticipated from the implementation of each candidate plan for signalization. This allows an objective decision process to be employed. That is, the solution may not be cost-effective if a relatively small benefit is to be expected. Normally, this is not the case in considering traffic signal improvements, in that the payback has classically proven to be high. However, it is important to perform the analysis and to estimate the benefits conservatively. Criticisms have been made that improvements have not met expectancies; however, it is possible that benefits were not achieved. It is also possible that the expectancies were established at an unreasonable level, perhaps, in an effort to sell a program. The payback on traffic control improvements is normally so high that it is unnecessary to oversell the results (*2*).

As with any improvement program, the second element of benefit analysis is a comparison with costs. Estimated costs should include not only procurement, but design maintenance and operating cost as well. It is important to consider the period in which actual procurement is expected, so that inflationary tendencies be recognized. It is also important to consider cost trends. For example, it appears that the cost of electro mechanical equipment is increasing at a rate which exceeds solid-state equipment, while solid-state components have been decreasing in cost in recent years. These trends may indicate that Model 170 controllers or NEMA-type could become more competitive, while other less sophisticated units could become less competitive (*7*).

Too often, the initial cost of the signal installation may outweigh all of the criteria that rightfully should be used in controller selection. The traffic engineer should strive to avoid that pitfall. Over the past several years, signal controller prices have generally declined, while reliability, versatility, and innovative features have increased. Generally, the relatively small price gap between "cheap and dirty" and the proper controller for the job at hand represents a small enough percentage of the total installation cost that it should not even be a factor. On the other hand, the traffic engineer need not overdesign in his selection of traffic signal control. If no need exists in the foreseeable future for a full-feature or multiphase unit, one that really fits the task should be used.

Maintainability and Reliability. The capability of the agency's maintenance and operation staff must be considered in control selections. The training requirements associated with procuring any new equipment is a critical element. Standardization to avoid continual retraining is one approach to minimizing the problem. Low-cost purchasing may lead toward larger scale procurements, such as packaging several projects into a single program or use of annual controller equipment procurement procedures. Several larger agencies have used the annual procurement process as an effective way of minimizing problems with multiple manufacturers of similar equipment.

Reliability is often not only design-related but may also reflect quality control during manufacture. Continuing emphasis must be placed on ensuring minimum electronic requirements for components and then using test procedures to guarantee quality control during fabrication. Controller selection should include consideration of the reliability of similar equipment previously furnished. Most importantly, the agency must have the capability, in-house or elsewhere, to access reliability; that is, the capability to adequately test the equipment before it is placed on the street (*2*). For users of the Model 170 controller system, the Self-Testing Evaluation Program (*10-12*) is available for such procedures. Bid proposals for equipment might also contain conditions under which acceptance test procedures by the user can be undertaken before units are considered for purchase.

Implementability and Flexibility. The user must determine whether or not the controller and/or system selected can be practically applied to a particular task. The user should also ask questions such as the following:

- Can the desired control be effected without unit modification(s) by someone other than the manufacturer?
- In considering a system, are individual controllers capable, without major modification, of controlling any intersection in the system?

- Considering the possibility of future intersection control operation expansion, can the controller be easily adapted to cover additional phases and/or reordered intervals or phases?
- Can isolated-type controllers, which may become part of a future system, be converted easily for interconnection by the selected medium?

Human Factors

In selecting a controller or controller system, the user must not overlook human factors. To the highest practical degree, the equipment under consideration should be engineered for simplicity and ease of human operation and maintenance. The phrase "user friendly," usually heard these days in relation to the more sophisticated electronic gear, certainly is applicable. Perhaps the best measure of human factors in selection of equipment is an in-depth look at the experience, capabilities, and even the attitudes of the traffic engineers, technicians, and other maintenance personnel. Their operator-machine interface with the equipment under consideration is literally the human factor.

REFERENCES

1. Kell, James H., and Iris J. Fullerton. "Manual of Traffic Signal Design." Institute of Transportation Engineers, Washington, D.C., 1982.
2. Tarnoff, P. J., and P. S. Parsonson. "Selecting Traffic Signal Control at Individual Intersections." NCHRP Report 233, Transportation Research Board, NRC, June 1981.
3. "Manual on Uniform Traffic Control Devices." Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1978.
4. "Traffic Control Systems." Standards Publication/No. TS1-1983. National Electrical Manufacturers Association, Washington, D.C., 1983.
5. "Type-170 Traffic Signal Controller System — Hardware Specifications." FHWA-IP-78-16, Federal Highway Administration, Washington, D.C., 1978.
6. "Local Intersection Program (LIP) — User's Manual and Software Documentation." FHWA-IP-79-10, Federal Highway Administration, Washington, D.C., 1979.
7. "Diamond Interchange Program (DIP) - User's Manual." FHWA-IP-80-4, Federal Highway Administration, Washington, D.C., 1980.
8. Gibson, David R. P. "Status Report on the Type-170 Traffic Signal Controller System." HRP-20, Federal Highway Administration, Washington, D.C., 1984. (Article.)
9. "Type-170 Coordination Program, Basic Arterial System (BASYS)." California Department of Transportation, Sacramento, California, 1982.
10. "Self-Testing Evaluation Program." FHWA-IP-84-1, Federal Highway Administration, Washington, D.C., 1984.
11. "Acceptance Test Manual, Type-170 Traffic Signal Controller System." Implementation Package, Federal Highway Administration, Washington, D.C., August 1984.
12. "Maintenance Guidelines." Implementation Package, Federal Highway Administration, Washington, D.C., August 1984.
13. Haenel, Herman E.; Alfred H. Kosik; and Blair G. Marsden. "Innovative Uses of Traffic Responsive Control in Texas." Presentation Paper, Engineering Foundation Conference, Henniker, New Hampsire, July 1983. State Department of Highways and Public Transportation, Austin, Texas.

7. SYSTEM MASTERS

CONTENTS

Section *Page*

7.1 INTRODUCTION 7.3
  Function 7.3
  Historical Perspective 7.3
    Electromechanical Masters 7.3
    Analog Computer System Masters 7.4

7.2 ARTERIAL AND SMALL NETWORK SYSTEMS 7.4
  Actuated Coordination Units 7.5
    Description 7.5
      Features/Capabilities 7.5
      Application 7.5
  Masters in Arterial and Small Network Systems 7.6
  Arterial Master Systems 7.6
    FACTS System 7.6
      Features and Capabilities 7.6
      Application 7.8
    DARTS System 7.8
      Features and Capabilities 7.8
      Application 7.10
    Basic Arterial System (BASYS) 7.10
      Features and Capabilities 7.10
      Application 7.11
  Manufacturers' Arterial/Small Network Systems 7.12
    LFE/Automatic KB200 Master System 7.12
    Eagle MC880 System 7.12
    Safetran Model 170 Arterial System 7.12
    Safetran CM1630 System 7.13
    Econolite EMC-10,000 System 7.13
    PRC Voorhees Micro Control System 7.13
    TRAC System 7.13
    Traconex HMM-200 System 7.14

7.3 TIME-BASE COORDINATION 7.14

7.4 DISTRIBUTED, CLOSED-LOOP SYSTEMS 7.15
  EDIPS, Model 170 System 7.15
    Features and Capabilities 7.16
    Application 7.18
  JHK Distributed Traffic Control and Surveillance System 7.18
    Features and Capabilities 7.18
    Application 7.20
  Transyt 3800 Closed-Loop System 7.20
    Features and Capabilities 7.20

229

Section *Page*

Application 7.21
Econolite KMC-10,000 Master System 7.21
Features and Capabilities 7.21
Application 7.23
Safetran CM1655 System 7.23
Features and Capabilities 7.23
Application 7.23

7.5 BASIC COMPUTERIZED SIGNAL SYSTEM 7.25

7.6 UTCS SOFTWARE 7.25
First-Generation Extended and Enhanced Software 7.28
1½-Generation Control (1½-GC) 7.30

7.7 NETWORK CONTROL SYSTEM MASTERS 7.31
Custom-Designed Systems 7.32
Package-Type Systems 7.32

7.8 OPTIONAL CONTROL AND OTHER SOFTWARE FEATURES 7.34
Preemption 7.35
Unattended System Operation 7.35
Equipment Malfunction Detection and Failure Reporting 7.35
Backup Techniques 7.36
Controller Down-Loading and Up-Loading 7.36
Memory Overlay and Background Data Processing 7.37

7.9 CONTROL CENTER FEATURES 7.37

7.10 SOFTWARE AVAILABILITY 7.39
Private Sector 7.39
Public Domain 7.40

REFERENCES 7.40

7. SYSTEM MASTERS

7.1 INTRODUCTION

A system master is defined as a control unit which provides universal electronic output to supervise one or more local controller units which, when taken together, comprise a traffic signal system. Hereafter, the terms "master," "control system master," and "master unit" are used congruently with "system master." In larger traffic signal systems, the system master may range from field-located units to a central master unit housed in a transportation management center.

This chapter deals with concepts and hardware associated with coordinated control of traffic signal systems. The two basic types of traffic signal systems are as follows:

- An arterial (open network) system in which signals in a linear pattern are supervised to give progressive flow in one or both traveled directions
- A network (closed grid pattern) system in which several arterials, forming an interlocking pattern, are supervised to give, as practicably as possible, progressive flow in all traveled directions within the network

Function

The use of a system master implies the concept of supervision of local controller units by a master or central master unit via some type of communication link (1-way communication). The communication link may also provide for transmitting traffic data to the master or central master unit from the locals, in order that control decisions can be made or surveillance information can be displayed (2-way communication).

Because of technological developments during the past several years, system-type control is possible without the above described communication link. During the late 1970s, a device known as a time-base coordinator was developed for use in supervising local controller units to establish pseudo system coordination. This device relies upon a very accurate quartz clock which references from the 60-cycle AC line frequency and emulates master control of each local unit. The features and capabilities of this device are covered in a later section of this chapter.

Historical Perspective

Early signalized intersection control involved the installation of pretimed electromechanical controllers at isolated intersections. Not long after, it became desirable to obtain some type of time relationship between adjacent signals, to assure progressive flow of traffic in an open or closed network. In the late 1920s, wire pairs were used to interconnect induction motors in local control signal towers to establish timing relationships between intersections. One of the early methods of establishing progression timing was to install synchronous motors in local controllers. Thus, the timing dials driven by the motors at each local would rotate at the same speed providing the same cycle length throughout the network. By the use of a stopwatch and the start/stop switch for each local controller motor, desired offsets could be achieved at each location. The basic problem encountered with these relatively primitive systems was that offset relationship between locals was easily lost whenever power failures or voltage fluctuations occurred. Thus, considerable maintenance was required in the form of manually reestablishing offset references.

Electromechanical Masters. The next step in signal system development was to link the local controllers with a master control mechanism via a 2-conductor parallel circuit. Thus, through the use of a reset feature, the master control mechanism could supervise the locals, maintaining an offset relationship between them on a common cycle length. This single-reset system, as it came to be known, assured that local dials were in step with central control at the beginning (end) of each system cycle. If the reset key on a local controller reached the 12 o'clock (offset reference) position ahead or behind the reset (release) pulse from the central unit, the dial was stopped at the local 12 o'clock position by its brake coil. The dial remained at the reset point until the release pulse from the central or master unit occurred, restarting the local dial at the proper system offset point. This system offered a simple but effective means of implementing a single timing plan for a signal system (*1*).

The next logical step came about because at least three (traditionally a.m., off-peak, and p.m.) timing plans were needed to provide some flexibility in serving varying traffic demand. The result was the development of the triple-reset system. The principle was the same as single-reset, except that 3 separate reset keys and 3 respective

231

brake coil circuits (returned to master unit) were provided at each local controller. Then, of course a 4-conductor parallel interconnect circuit was required. By means of a single pole, triple-throw selector switch at the central mechanism, one of 3 possible resets (a.m., off-peak, p.m.) could be manually selected. The 3-position switch was sometimes time-clock enabled. The major disadvantage of the triple-reset system is that only a single cycle length is possible. The flexibility of triple-reset was increased by providing a means of varying the cycle length. This was done by slowing down or speeding up the dial rotation, thus increasing or decreasing the system cycle length. A master timer was introduced into the system to interrupt, on a selective basis, the electrical circuits. In this manner, it was possible to vary the cycle length (*1*).

The final step in the development of an electromechanical system master unit provided a means of implementing multiple timing plans (cycle, offset, split) for the system. This approach to timing is accomplished by utilizing multidial master or master-secondary and local controllers. Up to 3 dials are used in each controller. For each of the 3 dials (each usually set up for a different cycle length and split), 3 different resets are available. Some controllers also provide for 3 different splits per cycle. Thus, considerable flexibility for timing plan implementation is provided since as many as 9 combinations of offset and cycle split are available, and these combinations can be modified by utilizing different cycle lengths. Compared to state-of-the-art technology, the electromechanical 3-dial master concept is very simple, but many of these reliable systems which are widely used remain in service today. In many cases, electromechanical system local controllers have been converted to work in conjunction with a digital computer as the central (system) master, thus overcoming some of the disadvantages normally associated with original systems operation.

Analog Computer System Masters. The next class of system masters could be termed the electromechanical/analog system. It was developed to make network signal control more flexible and responsive to actual traffic flow, as well as providing limited surveillance capabilities in terms of traffic flow data and system operation. Perhaps one of the most familiar systems of this type is the PR system (*2*) A brief historical review of that system follows, as an example of central master system control utilizing an analog computer.

The PR system was developed from the electromechanical system discussed earlier through the addition of sampling detectors and an analog device, which provided a means for making the system traffic-responsive. The PR system was designed for control of arterial (open) or closed networks. The system was designed to detect and respond to three basic traffic flow conditions: inbound, average, and outbound.

Offset timing was available for each of the three conditions. A fourth offset (simultaneous operation) was available for traffic saturation volume levels. Local controllers provided for 3 different cycle splits, which could be associated with any of the offsets. Any of 6 preselected cycle lengths could be chosen by the central computer, depending on the volume levels being detected. Thus, the PR system was capable of responding to traffic flow by automatically selecting various combinations of 6 cycle lengths, 4 offsets, and 3 cycle splits, in accordance with the traffic flow measurements received from the sampling detectors.

The PR system, by introducing some new concepts in system master control, provided the traffic engineer with additional equipment flexibility. Pertinent aspects of the system are summarized as follows:

- Represented the use of an analog-type computer to introduce automated decision-making in system traffic control
- Provided for receipt of traffic flow data from selected sampling locations and utilized these data to change the system timing plan if necessary
- Provided a system of generating varying current frequencies at the central control location and of transmitting the selected frequency through cable interconnect to drive local controllers, also offering a first opportunity for central control (manual or automatic) of cycle length
- Provided a combination of 6 cycle lengths, 4 offsets, and 3 cycle splits that could be used to specify system timing plans

The use of an analog-type central master in the PR system was a significant step in the direction of more traffic-responsive control systems, and it set the stage for the use of digital computers as system master units.

7.2 ARTERIAL AND SMALL NETWORK SYSTEMS

An arterial street signal system forms what is termed an open network. The basic concept of an open network signal system is that vehicles traveling along the arterial are released in a platoon from each signal and travel then in a platoon to the next signal. It therefore becomes desirable to establish a time relationship between the beginning of arterial green at each system intersection, in order that traffic platoons may proceed with the least possible delay and in the most orderly manner possible along the arterial.

The concept for control in small network systems is much the same as that for the open network. However, the arterials now cross each other, and interrelated timing considerations are introduced. Master control hardware for arterials is usually applicable to small network systems.

Actuated Coordination Units

The coordination of full-actuated or semiactuated controllers in arterial and open network systems requires a series of commands during each cycle. In a pretimed system, the only cycle-oriented command is a sync pulse, because all intervals of the local cycle are of a fixed duration. The phases under actuated control vary in response to detected traffic demand at the local intersection, and additional cycle-oriented commands are required to facilitate supervision by a master controller.

Description. Coordination units for actuated controllers in a system originally were similar to the dial units used in electromechanical controllers. The local coordinators were maintained in correct offset relationship by a system master dial, in much the same way as in the previously described pretimed coordinated systems. One or more keys, located at designated positions on each local dial, were then used to issue the appropriate local control command (yield, hold, force-off). State-of-the-art coordination units are now of solid-state design, and they are resident within the local controller assembly. Their theory of operation, however, remains as described above, though they have greater flexibility through a larger selection of cycle lengths, offsets, and cycle splits.

Features/Capabilities — Typical solid-state coordination units for actuated local controllers offer the following features:

- Six dial (cycle) selections
- Four splits per cycle in operation
- Five offsets per cycle selected
- Two variable permissive periods per cycle selected
- Eight force-offs per cycle selected
- Programmable Max II selection
- Auto-revert to standby mode, or last program called for, upon loss of interconnect
- Auto-revert to free operation upon loss of system sync

The coordination units provide the commands to the local controller unit, according to the master unit-selected timing plan in effect at any given time. These commands which are time-structured occur during each cycle to assure a guaranteed green interval for the coordinated (nonactuated) phases, and during selected time slots for the remaining (actuated) phases. The basic commands sent to the local controller during each (background) cycle are as follows:

- Force-off — A command which is issued to begin termination of an actuated phase. Each assigned force-off point is located precisely in the background cycle. It is sent to the controller only under the following conditions:
    - If its respective phase is called and serviced
    - If calls on the phase continued to (and beyond) the force-off point
    - If calls are present on any of the subsequent scheduled phases

  The last (actuated) phase force-off occurs only if the above listed conditions are met. If calls on any of the actuated phases terminate before the scheduled occurrence of the force-off and demand is present on the next phase, the demanding phase will be served earlier than scheduled in the background cycle time frame.
- Hold — A command which is issued to guarantee a certain minimum of green time to a phase. Normally, it is used in the coordinated phase to guarantee a window of time in the background cycle for traffic progression on the major street. Thus, the coordinated phase is considered nonactuated because its duration is not reliant upon vehicle calls. A hold command can be applied to a phase other than the coordinated phase.
- Yield — By de-energizing the Hold command, the resulting yield condition begins the termination of the active phase. The yield condition, which is no longer recognized by NEMA as a command per se, is usually associated with the coordinated phase, and in the absence of demand on other (actuated) phases, the controller remains in coordinated phase green. The yield (or permissive) condition may be programmed for a certain duration. If a call subsequently appears on any of the other (actuated) phases during the yield condition, the calling phase would, conditionally, be serviced. The condition for servie is that sufficient time remains before the calling phase's scheduled force-off command occurs.

Application — Coordination units provide the means for implementation of master controller unit commands (as above described) on the local controller unit level. When full- or semiactuated controllers are used in a signal system, coordination units may be required, but some state-of-the-art controller units have built-in coordination unit functions.

Masters in Arterial and Small Network Systems

The master controller in an arterial system or small network may be as simple as the pretimed single-dial electromechanical controller described earlier in this chapter. It could take the form of an analog device as used in the PR system. In state-of-the-art applications, the master controller is microprocessor-based, and it is capable of a multitude of functions above and beyond the basic transmission of sync pulses to system locals. It usually is capable of a time-of-day, traffic-responsive, or manual implementation of timing plans. In the traffic-responsive mode, the master can interrogate several sampling detector stations and make intelligent system-cycle, offset, and cycle/split decisions based on volume and/or occupancy calculations. Some masters also have the ability to store detector count data for later printout. A configuration for 2-way communications offers the capability for local controller unit feedback. Although the central control computer concept is sometimes applicable to smaller networks, and indeed there are many examples in operation, most arterial and small network master units are street-cabinet housed. In this context, there is little operator interface with the units on even a daily basis. However, as the following text unfolds, the reader will see that several of the small systems have some interface capabilities and functions formerly limited only to full-blown central-computer-operated, large networks.

Arterial Master Systems

Covered in this subsection are systems which utilize a master controller (or one or more coordination units to supervise arterial locals), but might have application in crossing arterial or very small network systems. Each system described carries its control concept beyond the basic master/local control previously covered, in that the function of system surveillance now enters the picture.

FACTS System *(5)*. The Flexible Advanced Computer Traffic Signal (FACTS) system was developed by traffic engineering and computer personnel of the Texas Department of Highways and Public Transportation. The FACTS system is designed for traffic control of arterial streets, frontage roads, or grid patterns having multiphase, pretimed, and actuated signals. System logic was primarily developed from concepts and algorithms contained in the UTCS software developed by FHWA, from ASCOT software developed in NCHRP Project 3-18, and timing patterns resulting from PASSER II, an off-line signal optimization program developed by the Texas Transportation Institute. Basic hardware for the system includes a 24K digital computer (Data General NOVA 1), CRT (or other input/output device), paper tape reader, NEMA-type, actuated local controllers, communication lines, necessary communication interfaces, and system detectors. Figure 7.1 is a block diagram of a typical hardware arrangement.

Features and Capabilities — The FACTS system has the following features:

- Time-of-day/day-of-week event schedules by which the operator may schedule TOD/DOW, traffic-responsive, or isolated system operation for designated time periods per respective day.
- Manual override — Traffic pattern — System mode, by intersection, if desired.
- Responsive pattern selection — Cycle length, offset levels, and splits selectable independently from a mix of detectors and control parameters.
- Detector failure monitoring — Based on volume and occupancy thresholds set by operator with default values triggering TOD pattern selection when detectors fail.
- Local controller failure monitoring — Based on response received by the computer from the local controllers (green-confirm per phase).
- Subsystem control — Locking of adjacent subsystems on same cycle length — Reconfiguration, by intersection, operator-selectable.
- Detector assignment — Operator-assigned detector(s) to selected subsystem for selection of traffic-responsive patterns.
- System status — Operator-controlled output for current system mode, pattern(s) in effect, and controller (detector failures).
- Variable phase sequence — Different patterns can have different phase sequences, by intersection (i.e., both the arterial and the cross street may have the following: LT first, directional lead/lag LT, or through movements first).
- Local control options — On an intersection basis, phase skipping and gap-out are operator-selectable per timing plan.
- Floating background cycle timers — Enables system to change patterns smoothly and rapidly — Transition from one pattern to another sets background timer to the offset of the new pattern, to the signal that first times out its cycle. Offset implementation begins as other signals reach the end of their respective cycles.
- Variable pattern transition — In addition to short-

234

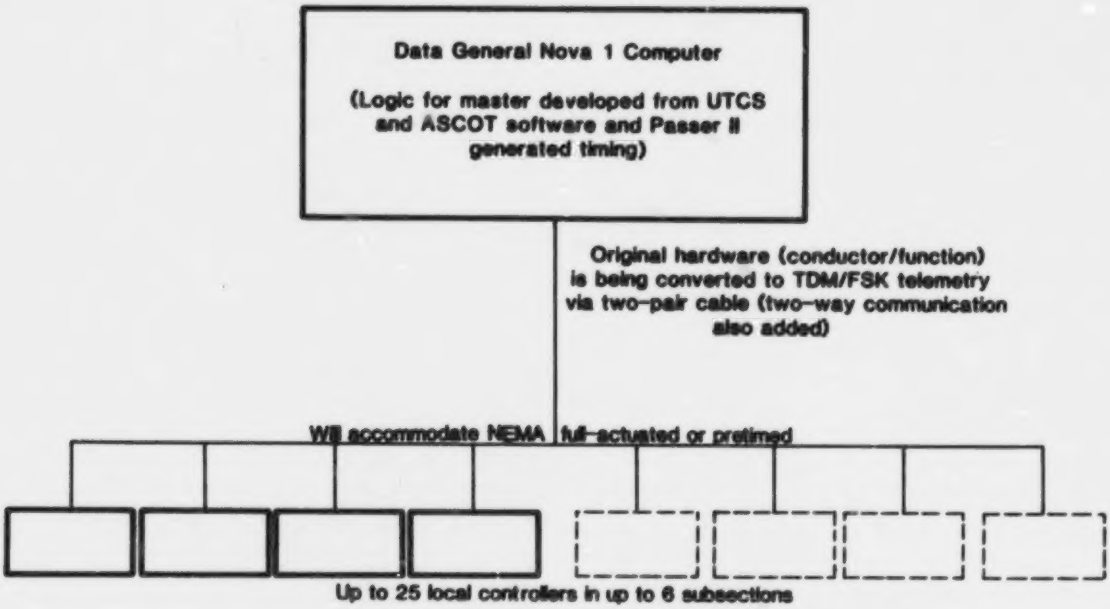

Data General Nova 1 Computer
(Logic for master developed from UTCS and ASCOT software and Passer II generated timing)
Original hardware (conductor/function) is being converted to TDM/FSK telemetry via two-pair cable (two-way communication also added)
Will accommodate NEMA full-actuated or pretimed
Up to 25 local controllers in up to 6 subsections

Figure 7.1. Block diagram of flexible advanced computer traffic signal (FACTS) system

Source: Reference (*5*)

way transition, the user has the option to program the break at other than 50-51 percent; normally, 30-70 percent is used, so that cycle-length decreases or increases can be handled efficiently. The user also has the option to transition some patterns more rapidly than others (e.g., a pattern designed to handle a sudden surge can be programmed to transition in a single cycle while others can transition more slowly with less traffic disruption) (*5*).

- If a controller unit is on flash, it can either be placed back into system operation or into free operation, by command from the central control point.

The FACTS system hardware and software provide expansion for controlling a total of 25 traffic signals operating in up to 6 subsystems, with a total of 188 traffic patterns that can be provided for each of the subsystems. Included are up to 6 splits for each of 32 cycle-length offset patterns. A traffic pattern is selected, with the system in the traffic-responsive mode, as follows:

- Cycle length is determined from volume plus occupancy data received from selected detectors. The phase sequence for each multiphase intersection is associated with the cycle length.
- Next, the offset, based on volume plus occupancy from a selected set of detectors, is chosen. The detectors need not be the same as those used for the cycle-length determination.
- The split is then selected from a set of detectors respectively assigned for that function.

The system uses a combination of the 2 most recent 3-min sampling periods. Cycle length and offset can be changed at the end of the two most recent sampling periods. Splits can be altered per sampling period. A 1½-GC version of the FACTS system has been developed for arterial streets using the PASSER II-80 as the pattern generator. This version is designed for automatic development of traffic plans which can be compared with existing plans, selected if desirable, and then downloaded to the computer for implementation (*5*).

The FACTS system also has many interrogation and diagnostic features. Via dial-up telephone, maintenance personnel can obtain complete system operation status reports, and can issue some local operational commands. The status reports include the following:

- System detector failures

- Intersection detection failures
- Intersection online or offline
- Local phase problems
- Computer systems status checks
- Local conflict flash conditions

Commands to correct local operation are as follows:

- Reset conflict monitor (if in conflict flash)
- Place phase on recall (if detector is malfunctioning)

Additional features are planned for the central interrogation of local controller units, including intersection manual flash operator and detector loop diagnostics (*15*).

Application — The first FACTS system was placed in operation in 1979. Two examples of its system application are as follows:

- The NASA 1 system — NASA 1 is a 4- and 6-lane divided arterial with channelized left turns. The arterial signal system consists of 6 intersections located within approximately 1 mi. NASA 1 carries 55,000 ADT with cross-street volumes ranging from 4,500 to 14,500. Traffic generators include the NASA complex, office complexes, apartment, extensive commercial strip development, and a large residential area. All signal controllers are expandable, full-actuated NEMA units; two 8-phase, three 3-phase, and one 2-phase. In 7 locations, 20 system detectors are utilized for cycle, offset, and split determination. This system also has 1½-GC capabilities, and utilizes PASSER as the offline program for optimizing signal plans.
- An evaluation study of the NASA 1 system, which compared computerized control with the original isolated full-actuated control, showed that fuel and time savings resulted in a 13.5 to 1 benefit/cost ratio. Stops and delay both improved 38 percent (*15*).
- The State Highway 225 system — SH 225 is located in the same vicinity as NASA 1, near Houston and just east of U.S. 75. The system is located along a future freeway facility for which only the frontage roads have been constructed. The median separating the frontage roads varies between 145 and 315 ft. Six signalized interchanges comprise the system which covers a 2.72-mi distance. Each frontage road is 2-3 lanes wide, with ADT at 33,000. The volumes on the cross streets vary from 7,500 to 13,000 ADT. Traffic generators include several petrochemical plants, operating three shifts on a 24-hr basis, whose only access is SH 225. Each interchange controller is a NEMA-type with special microprocessor software which permits use of 3-phase or 4-phase Texas diamond phasing, or allows each undivided intersection to run free as a single ring unit. Some 18 system detectors are placed strategically in the system for a determination of cycle length, offset, and splits, when operation calls for the traffic-responsive mode (*5*).
- Significant improvements were demonstrated by an evaluation study of the SH225 system. When operated under computer control, the stopped delay, travel time, and number of stops were reduced by 20 percent, 16 percent, and 54 percent, respectively. Considering the reduced fuel consumption and time savings for motorists, a benefit/cost ration of 9 to 1 was calculated.

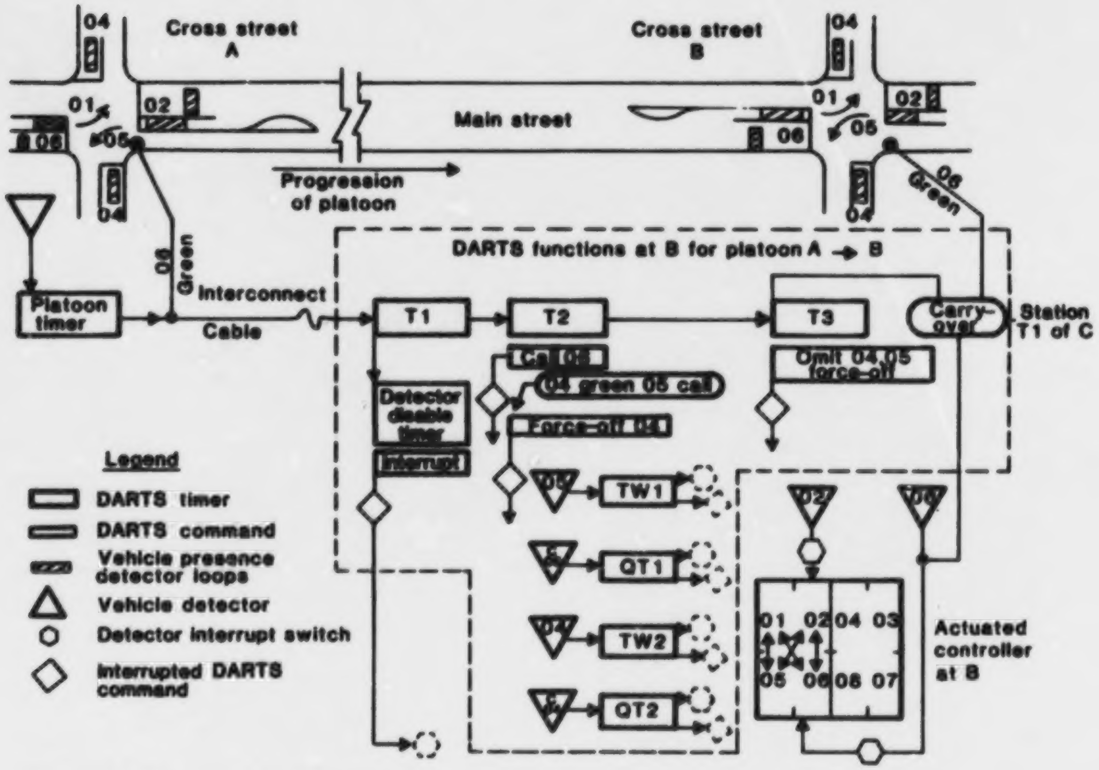
Other applications of the FACTS system include the control of 6 intersections in a grid pattern in the City of Fort Worth, Texas; system control along two arterial streets in Corpus Christi using a combination of full-actuated and pretimed controllers; and along FM1960 north of Houston, Texas.

DARTS System (*5*). The Dynamic Artery Responsive Traffic Signal (DARTS) system consists of a series of NEMA-type, full-actuated traffic signals, each with an external logic modular coordination unit. Although the system has been used for two crossing arterials, its application is normally limited to simple linear-type systems. The DARTS system was developed by San Antonio district personnel of the Texas Department of Highways and Public Transportation. Although it is commercially available from two manufacturers as a packaged system, DARTS remains public domain. The system permits each local controller to function in its normal isolated, full-actuated mode until a platoon (queue) is detected along the arterial at an intersection. Platoon coordination is then achieved on an intersection-to-intersection basis. DARTS is designed for systems in which long progression platoons form, where intersections are separated by moderate to long distances, and where turning movements, pedestrian calls, and cross-street volumes are low, or the ratio of cross street to arterial traffic is low. Each local controller in the system can be a 2-, 3-, 5-, or 8-phase unit (*5*).

Features and Capabilities — The intersection-to-intersection coordination described is achieved in the DARTS system through the following procedure (see Figure 7.2):

- A static platoon is recognized at Cross Street A by a line of cars queued, during the red, across a detector located a specified distance upstream from the stop line (on Phase 6 approach).
- A start message is relayed from Cross Street A to B, via the interconnect cable, at the exact beginning of Main Street green (at Street A).
- The start message, received at Cross Street B, starts

236


Cross street A
Cross street B
Main street
Progression of platoon
04
01
02
05
06
08
Platoon timer
06 Green
Interconnect
Cable
DARTS functions at B for platoon A → B
T1
T2
T3
Carry-over
Station T1 of C
Call 05
04 green 05 call
Force-off 04
Omit 04,05 force-off
Detector disable timer
Interrupt
TW1
QT1
TW2
QT2
Actuated controller at B
Legend
DARTS timer
DARTS command
Vehicle presence detector loops
Vehicle detector
Detector interrupt switch
Interrupted DARTS command

Notes 1. Phases 2,4, and 6 may utilize pedestrian intervals.
2. A second set of timers for T2 and T3 is used to provide changes in speed (school zone).
3. TW is a time-waiting function.
4. QT is a queue-timing function.

Figure 7.2. Operational layout for dynamic responsive traffic signal (DARTS) system

Source: Reference (*5*)

the detector disable timer and T-1 timer (at B). The detector timer disables Phases 2 and 6 detectors, which terminates that phase and permits cross street (B) and Phase 5 left turns (conflict with soon-to-arrive platoon) movements to occur. When the detector timer times out, Phases 2 and 6 demand is again recognized.

- Interval timer T-1 continues timing. Its total duration represents a portion of the time required for the platoon to travel between intersections at a preselected average speed. Its sole purpose is to time an interval which begins the clearance timing functions of T-2 at the proper time.
- Interval timer T-2 is initiated as T-1 terminates. If Phase 6 is green, it will be maintained so, because the platoon has reached a point at which insufficient time remains to serve conflicting places and return to Phase 6 as the platoon arrives (at B). If Phase 4 is being served and demand appears on Phase 5, it will be served. The function of T-2 is to assure service of certain phases in a time frame commensurate with the platoon progression.
- Interval timer T-3 begins as T-2 ends its timing. If the controller is in Phase 5 or Phase 4, the coordination unit forces the respective phase to end as its minimum green times out. If Phase 4 is thus terminated,

Phase 5 is omitted. The coordination unit also dispatches a start message to the next downstream controller that a "carryover" platoon has started at B, thus initiating timing on detector disable timer and T1 at that intersection.

- The process is then repeated for subsequent intersection-to-intersection progression through the balance of the system.

Platoons can be generated at any intersection in the system and progressed through it. However, if a platoon is already in route, the start message is withheld until the two platoons can be compressed into one. This feature allows for a static platoon which may have been recognized at a downstream intersection, to move forward in proper relation to an oncoming carryover platoon (from an upstream intersection) so that both form a single platoon. Obviously, this concept is limited to handling reasonably sized platoons (*5*).

Application — Two examples of DARTS System application are described as follows:

- State Highway 218 in University City, north of San Antonio, Texas — SH 218 is a 5-lane arterial carrying some 23,000 ADT. The DARTS system involves 12 multiphase, full-actuated signals located along a 3.4-mi section of the roadway.

  An evaluation study with the DARTS System in operation showed an increase in the average speed for peak and off-peak traffic from 29 mph to 34 mph, and a decrease in the number of stops from an average of 3.9 to 0.8 in each travel direction (*15*).

- Ocean Drive in Corpus Christi, Texas — Ocean Drive is a 4-lane facility on the edge of the CBD, carrying 24,000 ADT. The system consists of four signals located along a 5,500-ft section of the parkway-type facility.

  The City of Corpus Christi evaluation study of the Ocean Drive system showed that; the number of stops decreased 28 percent, the travel time decreased 25 percent, and average speed increased 76 percent and 38 percent in respective travel directions (*15*)

Basic Arterial System (BASYS) (*6*). The Operational Traffic Signal Progression System (BASYS) was developed by the California Department of Transportation (Caltrans) and is Model 170 controller unit based. BASYS is structured to operate and control a system of pretimed or actuated controllers by time-base coordination, telephone pair interconnect, direct AC, or standard 3-dial AC line. Block diagrams in Figure 7.3 illustrate some applications of the BASYS software.

Features and Capabilities — BASYS is comprised of two independent, but compatible, software programs: Basic Arterial Master (BAM) and Basic Arterial Local Intersection (BALI). The two programs, when resident on their associated 2708 firmware (on a Model 170 traffic PROM board), and mated to the Local Intersection Program (LIP) software, carry out their designed functions of coordination and control.

BASYS programs, BAM and BALI, have been structured to operate either remote from each other (in separate controller units) or on the same PROM module. With both resident on the same module, time-base coordination is available. However applied, BASYS provides a wide degree of operational latitude:

- Seven control plans are selectable by BAM for implementation by BALI at the local controller — Each of the 6 system coordination plans has a background cycle length, individual noncoordinated phase force-off points and 3 offsets. The seventh plan is online (free) operation. Selection of plans and offsets is possible by TOD/DOW (10 events), traffic-responsive (volume level), police and manual master select.
- Functions as a master or local in standard 3-dial system — Also structured to operate full or semiactuated locals or to emulate pretimed, 3-dial/3-offset system (local or master unit). Operates system through hardwire cables or telephone pair(s) interconnect.

The BAM program, when placed in the PROM module of a Model 170 will supervise a coordinated signal system in any one of the following ways:

- Act as a master for 3-dial/3-offset units via AC direct-line (multiconductor), or coordinator-type interconnect (full-actuated controller units).
- Act as a master for Model 170 controllers via AC direct-line (multiconductor) interconnect.
- Supervise Model 170 controllers equipped with the BALI program (using modem 400's) via telephone or agency-owned paired communications conductor

The BALI program, when placed in the PROM module of a Model 170 unit, will interface with, and supervise, its Local Intersection Program (LIP). When activated, BALI software reads either an in-house or remote master by scanning an operator-selected mode of communication and implementing the proper master commands. BALI operational features include the following:

- Local coordination per master command to give:

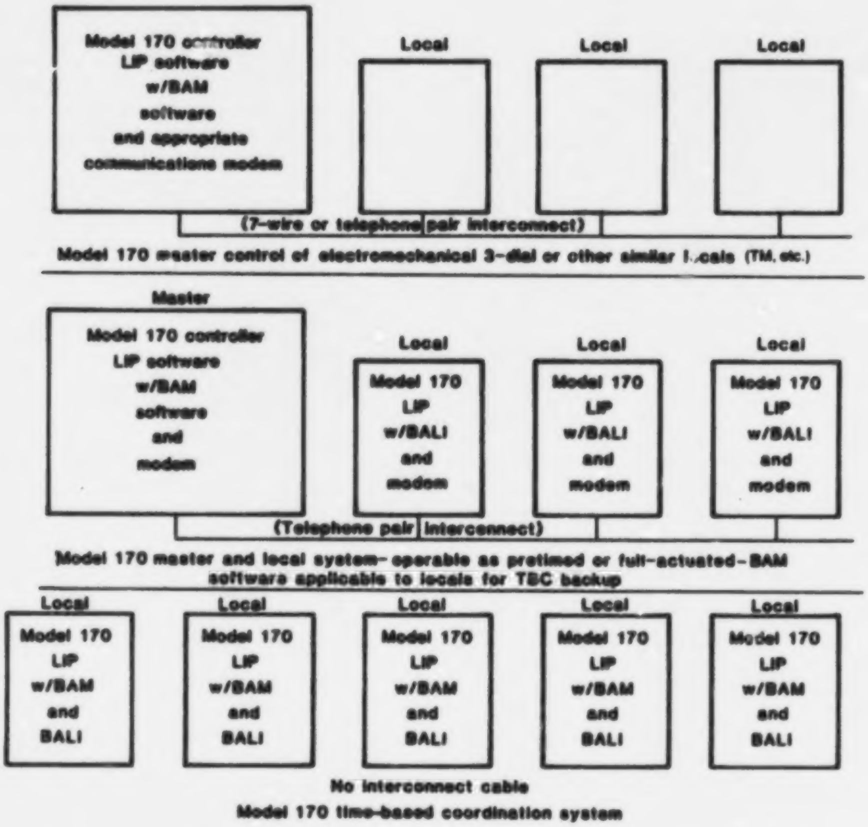

Model 170 controller
LIP software
w/BAM
software
and appropriate
communications modem
Local
Local
Local
(7-wire or telephone pair interconnect)
Model 170 master control of electromechanical 3-dial or other similar locals (TM, etc.)
Master
Model 170 controller
LIP software
w/BAM
software
and
modem
Local
Model 170
LIP
w/BALI
and
modem
Local
Model 170
LIP
w/BALI
and
modem
Local
Model 170
LIP
w/BALI
and
modem
(Telephone pair interconnect)
Model 170 master and local system- operable as pretimed or full-actuated-BAM software applicable to locals for TBC backup
Local
Model 170
LIP
w/BAM
and
BALI
Local
Model 170
LIP
w/BAM
and
BALI
Local
Model 170
LIP
w/BAM
and
BALI
Local
Model 170
LIP
w/BAM
and
BALI
Local
Model 170
LIP
w/BAM
and
BALI
No interconnect cable
Model 170 time-based coordination system

Figure 7.3. Examples of application of Basic Arterial System (BASYS) software programs

  - Online local free plan — normal or flash and provides for either; coordinated phases yellow (all other phases, red) or, all phases flash red
  - Six coordinated progression plans
  - Three offsets per plan
  - Eight phase splits per plan
  - One-time offset transition
  - One yield away per cycle
  - Left-turn lead-lag options
  - Phase settable as pretimed or actuated
- Local coordination time clock (online or offline), with 2 sets of selections per day-of-week (DOW)
- Operation in a variety of different systems besides BASYS (i.e., TM, 3-dial, diamond interchange and stand-alone, time-base coordination)

When installed together in a Model 170 controller with Local Intersection Program (LIP) software, BAM and BALI interact with each other and operate the local controller under time-based coordination thus emulating system control, without the physical interconnection of controllers (*6*). The BAM/BALI (local controller) combination can also be utilized as backup operation in the BASYS coordinated system configuration.

Application — If the user is considering the exclusive use of Model 170 local controller units in a control area or system, BASYS provides a good selection of system control concepts and strategies. Figure 7.3 illustrates some of the options.

Manufacturers' Arterial/Small Network Systems (3)

This section covers specific computer-based traffic control systems currently offered by manufacturers in the United States for the control of arterials and small networks. The brief discussions of each system are not intended to be comprehensive, and the respective manufacturer's current literature should be consulted for detailed information. Some of the systems described have undoubtedly received further refinements.

All traffic control systems designed for the control of networks can, of course, be adapted for arterial and/or small grid application. This section covers available systems geared to smaller scale applications.

Each control system narrative covers system features which are of operational significance. Features that vary widely, as a result of individual cities' desires, and, even among the same manufacturer's systems installations are not covered. Typical control applications which any given system might have, and which are easily definable, are also covered (*3*).

LFE/Automatic KB200 Master System. This system consists primarily of a smart master controller unit which can be used to supervise pretimed local controller units of various manufacturers. Up to 16 system detectors can be monitored to provide traffic-responsive operation based on volume or volume/occupancy parameters. Preprogrammed time-of-day (TOD), day-of-week (DOW) mode or manual control is also accommodated. The KB200 master unit provides for 3 cycles, 3 offsets and 4 splits (per cycle), or for free operation. System-detection sensors are continuously tested for reliability, and failed sensor data is removed from computations. Master-to-local interconnect options are 120-v AC or low-voltage DC.

Application for the KB200 Master System principally lies in the supervision of a small pretimed system consisting of a mix of existing local controllers of different manufacture, utilizing existing interconnect, but adding traffic-responsive capability and performance monitoring to the system (*3*).

Eagle MC880 System. This microprocessor-based system can serve in a stand-alone master unit mode, or as a submaster system to a central master unit or computer. Each implemented program or timing plan causes the outputs of 96 individual circuits to be turned off or on at respective times, specified by user-entered parameters. Thus each output circuit can be assigned to a specific function (such as force-off 1), and their operation (time on, time off) is independently programmed per respective plan. The master unit is designed for interconnection via direct-wire DC signal over voice-grade lines, and can directly control NEMA-type local units or supervise coordination units with single-function communications. External hardware can be added to the master unit to accommodate a time-division multiplex/frequency shift keying (TDM-FSK) communications system.

The maximum number of controllers that can be supervised by direct-wire DC control is dependent on the number of circuits required per local controller unit. Generally, an 8-phase NEMA controller requires at least 3 outputs for system operation. Based on that assumption, 32 local intersections could be included in a system interconnected by direct-wire control. However, the use of TDM/FSK, as described above would reduce wire pairs required and/or increase the number of local controllers comprising the system. Of course, the TDM/FSK system requires master and local encoding-decoding devices.

Up to 20 system detectors can be used to provide traffic-responsive operation, based on volume and occupancy measures. TOD/DOW and manual selection of timing plans is also accommodated. An extensive number of commands can be stored in the TOD/DOW program memory.

Applications for the MC880 System are versatile. If used as a replacement for a master unit in a system using local coordination units, the MC880 unit outputs could be used for selection of cycle length, split, offset, etc. Because the 96 output control circuits are individually programmable per timing plan virtually any small system configuration could be supervised with the MC880 master unit, utilizing the existing method of interconnection. Larger systems, or smaller systems, with more complex command requirements could also be supervised, by adding the external hardware necessary for TDM/FSK communications (*3*).

Safetran Model 170 Arterial System. This system utilizes Model 170 controller units for master and local control. All units are identical and interchangeable except for the software and cabinet used in respective the applications. The master controller unit can supervise up to 16 local units, through communication via full-duplex, voice-grade telephone lines.

Up to 16 system detectors can be handled by the master unit to obtain volume and occupancy measures for traffic-responsive operation. Timing plans are selected from a table look-up system in traffic-responsive mode. TOD/DOW and manual selection of timing plans are also accommodated.

The application of the Safetran Model-170 Arterial System requires the replacement of existing local controller units unless Model-170 units are already in service. The system could also be applied to small network operation (*3*).

Safetran CM1630 System. A 16-bit microprocessor-based master controller unit capable of independent control of two groups of intersections is utilized in this system. The master unit can be used as a submaster communicating, through TDM/FSK, with a central master or intelligent CRT terminal, or it can be used in the stand-alone mode. The master unit supervises 2-through 8-phase existing controllers, through TDM/FSK or hardware interconnect. Some controllers may require additional external interface logic and/or local coordination units. The master controls up to two independent groups of local units, and generates 3 cycle lengths, 3 offsets and 2 splits per cycle length, plus free operation or flash mode.

Volume and occupancy (VOC) surveillance is gathered from up to 16 system detectors for traffic-responsive operation. A VOC table selects timing plans based on smoothed VOC values in traffic-responsive operation. TOD/DOW and manual-select modes are also accommodated.

The application of the Safetran CM1630 system includes its use to supervise a large number of existing pretimed and/or actuated local controller units. Its capabilities for use as a stand-alone unit or as a submaster allows it to be used on-street for possible future utilization as part of a large distributed closed-loop system (*3*).

Econolite EMC-10,000 System. This system consists of a microprocessor-based master controller unit and local coordinator units for interface with existing full-actuated controller units. Communication for the system is via TDM/FSK, full duplex over 4-wire, voice-grade telephone-type cable. The local coordinator units generate appropriate commands to the controller. Control acquisition, smoothing transitions of offsets, and control failure diagnostics are functions accomplished by the local coordinators. The master unit is primarily a traffic-responsive coordination plan selector, but provisions for manual or external TOD/DOW override are included. System detector data are processed to compute level-of-service and offset, and one of 18 timing plans is selected based on these inputs to the timing plan matrix. The traffic-responsive timing plan-in-effect is selected from the highest priority source for which a control parameter is specified. Online manual changes of parameters, such as level-of-service, offset, and split for respective local coordinators, are operator-selectable.

The application of the EMC-10,000 system is the supervision of existing full-actuated controllers of various manufacturers through installation of the master unit and local coordinator units for each existing intersection controller. The system, thus formed, would be primarily traffic-responsive in nature, but manual and TOD/DOW timing plan implementation could be accommodated by the modification of the master controller unit (*3*).

PRC Voorhees Micro Control System. This system utilizes a 64K, personal-type computer as a master controller unit. Any NEMA-type, full-actuated, and various types of pretimed local controller units, can comprise the system. Up to 64 intersections, configured in 8 sections can be handled by the master unit, which uses a foreshortened version of the UTCS software for system control. Up to 32 detector stations can be monitored, but these are used only for collection of volume data.

The Micro Control System is capable of TOD/DOW and manually implemented timing plans, but it has no traffic-responsive capabilities. No MOE's are produced in the system. Controller status and malfunction, as well as detector failures, are system-monitored. Fifteen-minute reports on failures, volumes, and timing plan in effect are produced.

The application of the Micro Control System lies somewhere between a master control system which has no monitoring capabilities, and one which monitors volume and data for system MOE's and is capable of traffic-responsive operation. The system can be implemented by utilizing existing controllers of various types and of different manufacture (*13*).

TRAC System. This system utilizes a master controller unit and secondary controller units (at each local) which are microprocessor-based. Both pretimed and actuated controller units may be supervised through the use of force-off (or offset) signals issued by secondary units to terminate respective green intervals of each cycle, and to determine cycle length at each local intersection.

Two sets of volume detectors are placed at each approach end of the system to collect respective inbound and outbound data. Two occupancy detectors are also provided (each direction), and the highest value data from 1 of the 4 is used without directional consideration. In the traffic-responsive mode, the 2 volume detector sets are compared with each other to determine which direction (the heaviest) will be favored for system computations. Thus, traffic-responsive plans are constructed, based on collected data, on a cycle-by-cycle basis.

Time-of-day and the manual mode are also accommodated. A selection can be made from a group of 4 cycle lengths, 3 offsets per cycle, and 2 splits per cycle. Although the operational data base cannot be updated online, the system actually does not require stored traffic patterns or timing plans. The operational data base includes all volume and occupancy thresholds, system speed, speed modifications, cross-street split specifications, extensions per actuation for cycle-length computation, minimum and maximum arterial green times, and other operator-specified data. Monitoring, malfunction detection, and alarm generation are provided for system detectors and controller units via telephone dial-up interrogation. For instance, manual override can be implemented via telephone dial-up.

The TRAC system is best suited for the control of an arterial street section with actuated local controller units. The system can be comprised of any number of intersections, each requiring a secondary controller unit for supervision of the local unit by the master controller (*3*).

Traconex HMM-200 System. This system is designed to coordinate the operation of multidial controllers and actuated controllers having multidial coordination units. Controllers used as local units must be completely solid-state and have nonvolatile memory, such as the Traconex HMC-1000, HMP-190, or HMP-290 units. The master controller unit is a microcomputer which may be operated onsite or remotely. Data from up to 12 vehicle detectors may be received and processed by the master to determine vehicle and occupancy. Detector output is input directly into the master unit for processing. In the traffic-responsive mode, the TRSP algorithm selects 1 of 10 stored timing plans based on processed detector outputs. The pattern-matching, plan-selection calculation frequency is operator-selectable between 1 and 255 min. The master unit is also capable of TOD/DOW and manual-override operation. Up to 128 time commands per week, and up to 8 day-plans may be structured, utilizing a time command, for each day of the week. In the manual mode the operator may select dial, offset, split, flash, free or special function through an external facility control panel.

A battery-operated, 18-hour down-time accumulator is provided to preserve system timing parameters in the event of power failure. Failure monitoring of detectors by the master unit is done by checking minimum and maximum count against operator-input threshold values. A failed detector identified by operator as a key sensor causes the master to revert from the TRSP mode to TOD/DOW operation.

The application of the Traconex HMM-200 System is the supervision of existing pretimed or full-actuated controllers through the installation of the master unit and local coordinators for local-actuated controller units. Optionally, any or all of the existing controllers in the proposed system could be replaced with HMC-1000 or HMP-190 local controller units.

7.3 TIME-BASE COORDINATION

As was mentioned near the beginning of this chapter, system master control is possible without the use of either communication links or, for that matter, a system master unit. Several years ago, when a device known as a time-base coordinator (TBC) was developed to supervise local controller units, it established a new concept in system coordination. This type of device can be used in open or closed signal networks comprised of pretimed or full-actuated local controller units or a mixture thereof.

The TBC is a stand-alone unit which locally supervises a controller by the transmission of commands and sync pulses in much the same way as they would come via a communications medium from a system master unit. Equipped with a quartz-crystal, real-time clock which draws its accuracy from the 60-Hz powerline frequency, the TBC provides the same conceptual control available in a linked, master-controlled network. However, the installation of physical interconnect media is not necessary. Each TBC is equipped with a rechargeable battery to sustain full operating capability, except for output to the controller, in the event of power failure.

Although the features and capabilities of TBC units vary from manufacturer to manufacturer, their functional concepts of operation are quite similar, as described in the following:

- Clock units in most TBC units are of the one-week-base repeating type. Thus, there is no week-of-the-year setting on such units, and daylight savings or special events (date-oriented) cannot be programmed except on a one-week-notice basis. Some TBC's are equipped with one-year (52-week) clocks permitting the programming of events on a yearly (or shorter) time base.
- Most TBC's are capable of implementing at least 20 control plans, selectable from 4 cycle lengths, 3 offsets per cycle, 4 splits, flash, and time-of-week (year) control.

Depending on the application of the TBC unit, it is programmable to coordinate the following:

- Pretimed controllers using methods of cycle select, split select, and offset select, and providing the appropriate offset pulse for coordination

- Full-actuated controllers, 2-phase to 8-phase, using methods of cycle select, split select, and offset select, and providing yield/hold, force-off, omit phase, skip phase, and other related functions

Some TBC units have the capability of selecting variable phase sequencing (per timing plan) when used to supervise full-actuated, 8-phase controller units.

Smoothing routines for timing plan transition are usually included in TBC functions. On some units, these smoothing routine options are user-programmable, selectable from several options.

The TBC units utilize user-programmable memory for storing timing plan information and time-switched event information. The memory is usually programmable by using one of two methods: front panel keyboard entry in which the unit gives the programmer positive feedback to ensure each entry has been recognized and stored, and transfer of the full program from one unit to another of the same model by utilizing a transfer cable between units. If the program memory is accidentally erased, the TBC unit will automatically initialize memory for the implementation of a new program(s).

A perusal of the above text will show that the TBC is capable of performing the functions of most system masters. It is a very useful tool when the economic situation precludes the installation of cable interconnect to establish a needed signal system. This solution is especially valuable if the traffic engineer faces requirements or aesthetic considerations which mandate the use of expensive underground conduit to effect the communication link-up of controllers. Nevertheless, the use of TBC units is no substitute for a sophisticated control/surveillance type system, because information transfer between units is obviously impossible. However, because of its unique ability to emulate master commands without interconnection, the TBC concept is a viable substitute when economic constraints force a given system project overbudget.

The time-base coordinators from different manufacturers are compatible. A system can mix, for example, units by Eagle Signal, 3M, Traffic Control Technologies, or Winko-Matic, or even Model 170 controllers with internal TBC capability, and they will provide proper coordination. The potential user is advised, however, that all manufacturers do not orient their TBC units to the same zero base point. The user must assure that, when units are mixed in a system, a common zero base point is used throughout.

7.4 DISTRIBUTED, CLOSED-LOOP SYSTEMS

The closed-loop, distributed-processing control system concept utilizes one or more on-street, intelligent microcomputer submaster or satellite master controller units, each with the ability to select one of its stored signal timing plans, and to implement it by supervision of local controller units in its subsystem. Each submaster can function on a stand-alone basis, and primarily operates in traffic-responsive mode based on surveillance data gathered from subsystem sensors. Typical system elements are:

- System monitoring and input/output facilities at central office — Usually included are downloading and uploading of data to and from submaster units. Optionally, a personal size computer or a larger central microprocessor can be used.
- Communication links, which can range from telephone dial-up to one of several versions of standard dedicated media, utilizing some type of communication telemetry. Typically telephone dial-up or direct telephone lines are used between central office and submaster units, with more sophisticated, higher-capacity media used within the subsystem(s) between submaster and local controller units.
- On-street submaster or satellite master microcomputer units
- Subsystem oriented detectors
- Local controller units, usually fitted for time-base backup capability

The system is typically structured to provide for coordination of multiple subsystems from a central site. This concept suggests a building block design that permits future expansion (additional subsystems) without major modification to existing hardware.

Descriptions which follow are of systems of the distributed-processing, closed-loop design. However, each of them is unique, and they differ from one another in the specific control and surveillance features that are incorporated. The capabilities and functional approach of the control office master units employed are also different between systems.

EDIPS, Model 170 System (*10*)

The Eureka Distributive Intelligence Progression System (EDIPS) is a control system which provides coordinated control for grid and/or arterial subsystems. It includes 4 programs: Level 2 Area Control, Level 2 Display Master, Level 1 Supervisor and Local Intersection. EDIPS was developed by Caltrans and uses Model 170 controller

243

units throughout the system. Figure 7.4 is a block diagram of the system.

Features and Capabilities. The Level 2 Area Control includes the use of 2 Model 170 controllers as an operational system and intersection display unit, a CRT

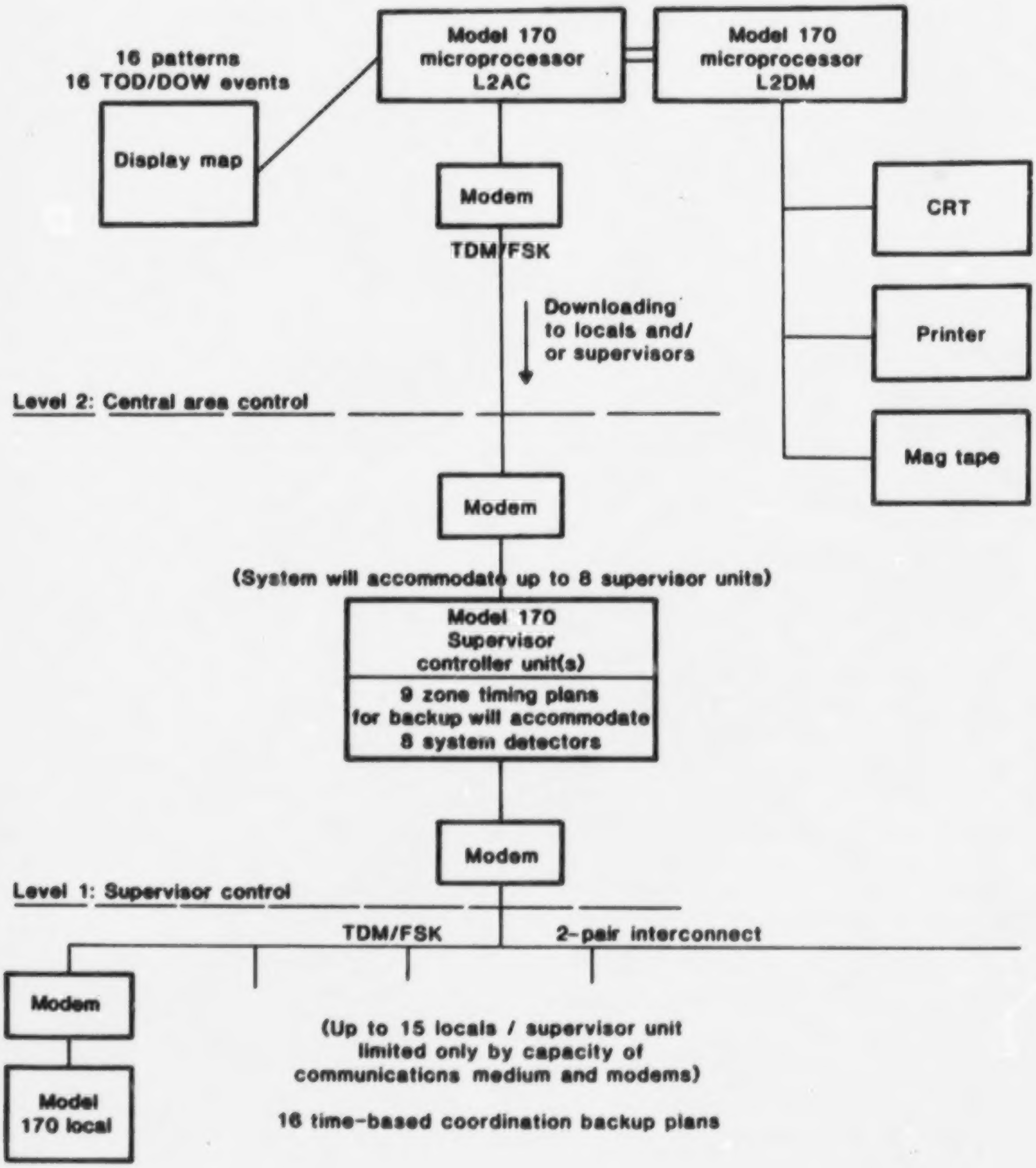

Model 170
microprocessor
L2AC
Model 170
microprocessor
L2DM
16 patterns
16 TOD/DOW events
Display map
Modem
TDM/FSK
CRT
Printer
Mag tape
Downloading
to locals and/
or supervisors
Level 2: Central area control
Modem
(System will accommodate up to 8 supervisor units)
Model 170
Supervisor
controller unit(s)
9 zone timing plans
for backup will accommodate
8 system detectors
Modem
Level 1: Supervisor control
TDM/FSK
2-pair interconnect
Modem
Model
170 local
(Up to 15 locals / supervisor unit
limited only by capacity of
communications medium and modems)
16 time-based coordination backup plans

Figure 7.4. Block diagram of Eureka Distributive Intelligence Progression System (EDIPS)

console, a printer and a cassette tape recorder. All equipment for Level 2 is mounted on a 6-ft-high, 19-in.-wide radio rack. Wall system map display driver software is resident. The 2 Model 170 controller units are interconnected by a wiring harness and function as follows.

- One of the units is designated Level 2 Area Controller (L2AC). Its associated resident program provides area control of the L1 supervisers, surveillance, report data gathering and processing, communications control and output control for system and intersection displays. The L2AC front panel is used for manual human interface, and for display of system and intersection status.
- The other unit is designated Level 2 Display Master (L2DM). Its associated program provides for control interface with system peripheral equipment. The L2DM is linked via connection to the CRT, printer, and magnetic tape recorder (secondary memory).

Together the L2AC and L2DM units perform the following system functions:

- Capability to request and display intersection or system status
- Receipt of data from assigned system detectors for TR pattern selection
- Provision of volume and occupancy data by gathering and processing information from system detectors
- Capability of detecting and identifying communications failures, individual phases at locals which have maxed out, and detector malfunctions
- Provision of operation interface for system display, report requests, and system changes and analyses

The L2AC provides system control via the control pattern and the system synchronization message sent to the Level 1 submaster controller units. The L2AC selects up to 16 system control patterns, 15 of which designate a Level 1 coordinated plan selection and one which is assigned for a free or unrestricted Level 1 Supervisor operation. The patterns are selected manually, or by time-event selection (based on historical data), or by traffic-responsive selection. The L2AC provides up to 16 time-event selection settings. The operator selects the time of day, and day of week that the desired patterns are to be implemented. The selection, once implemented, remains active until a new time selection is made. The L2AC scans up to 8 designated system detectors for settable sample periods when a traffic-responsive plan selection is called for. A pattern-matching technique is used for traffic-responsive selection where the closest match of values obtained during the sample period to operator set values is used to select the appropriate system pattern. Of the 3 methods of pattern selection, the manual selection has the highest priority. The next level can be either by the time-event selection, or by the traffic-responsive selection, as selected by the operator.

The Level 1 Supervisor (L1S) controller units will implement the area pattern (1 to 15) or free (0) that is transmitted to it once every cycle from the L2AC. This area pattern is matched against an operator-settable table at the L1S and a zone plan (1 to 9 or free), and an offset (1 to 3) is transmitted to the local intersection controller units for implementation. When the L2AC transmits pattern 0 (free) or there is a loss of communication between the L2AC and the L1S, the L1S will select one of the 11 zone plans or free operation for the local intersections in its zone based on either L1S time-event selection or L1S traffic-responsive selection, whichever selection method provides the highest plan number. The traffic-responsive selection routine operates concurrently with the time-event selection, and the traffic-responsive pattern selection will override time-event pattern selection anytime a higher numbered pattern is selected over that set for the time-event selection.

The L1S traffic-responsive plan is selected by averaging selected inbound and outbound detector values in the zone and comparing this value with operator-settable thresholds. The offsets for each plan are selected by comparing inbound and outbound traffic volumes to operator-settable values and selecting Offset 1 for inbound progression, Offset 2 for average progression between inbound and outbound traffic and Offset 3 for outbound progression.

The local intersection control program provides local intersection traffic signal control (up to 8 phases), coordination via a communications modem, emergency vehicle preemption railroad preemption and operation under standby event control settings which allow plan implementation or free unrestricted local intersection operation based on 16 time-of-day, day-of-week settings.

Coordinated operation utilizes a common background cycle length selected by interconnect with the Level 1 Supervisor controller unit. Nine operator-settable timing plans (cycle length, splits, and 3 offsets per plan) and free are implemented when called for by the Level 1 Supervisor controller unit. Upon a loss in communications between the local and the Level 1 Supervisor, the local will implement the plan called for by the standby-event control settings. The phase sequence may be changed from plan to plan to provide leading or lagging left turns as required for efficient 2-way progression or traffic. The required force-off times for each phase are calculated by the program based on the cycle length, the selected green times of noncoordinated phases, the yellow change interval selected, and the phase sequence selected.

Application. EDIPS offers a distributive intelligence, multilevel control system based entirely upon use of Model 170 controller units. The software programs for EDIPS are in public domain and will be available from Caltrans.

JHK Distributed Traffic Control and Surveillance System (9)

The control center of this system is similar in its hardware concept to traditional master computer-type systems. Included in the control center complement are the following:

- Master computer with 256 to 512K RAM including assembly, BASIC, and FORTRAN language software. (Optionally, remote-terminal emulation software is included.)
- Monochrome monitor (CRT) subsystem
- Color graphics monitor (CRT) subsystem
- Hard disk subsystem
- 80 cps, dot matrix printer
- Floppy disk subsystem
- Appropriate modems to accommodate a selected communications system

Submaster controllers and local controllers are Model 170 units equipped with appropriate firmware and communications interface modems. Both local and submaster controllers are software-equipped for time-base coordination in on-line and backup modes. Figure 7.5 is a block diagram of the distributed processing, closed-loop system.

Features and Capabilities (9). The master microcomputer provides systemwide coordination and monitors system performance from a central location. Optionally, up to 32 personal microcomputer workstations may be attached to the central computer via a local area network. Each workstation has the capability of performing routines including the following:

- Traffic data analyses
- Control device inventory
- Traffic engineering analyses (including signal progression and traffic simulation programs)

The central monitoring facility transmits and receives data via dedicated or dial-up telephone lines, a coax network, or an RF communication network. The system and intersection diagnostic data are received from onsite submasters and locals. The resulting system reports include the following:

- Operational failure logging, initiated by messages received from submaster(s) or local controllers, and output via hard copy at the time of occurrence
- Detector volume summary, obtained via onsite submasters from selected as system detectors
- System status, received from submaster and local controllers, including current patterns in effect, mode of submaster(s) operation and equipment status
- Intersection status display of real-time information, presented on the color graphics CRT, for any selected system intersection. (Includes vehicle and pedestrian signals status, flash status, preempt on or off, and operation plan in effect.)
- Automatic downloading of all submaster operating parameters and local timing data with data disk-resident and loaded via the communication network through the keyboard

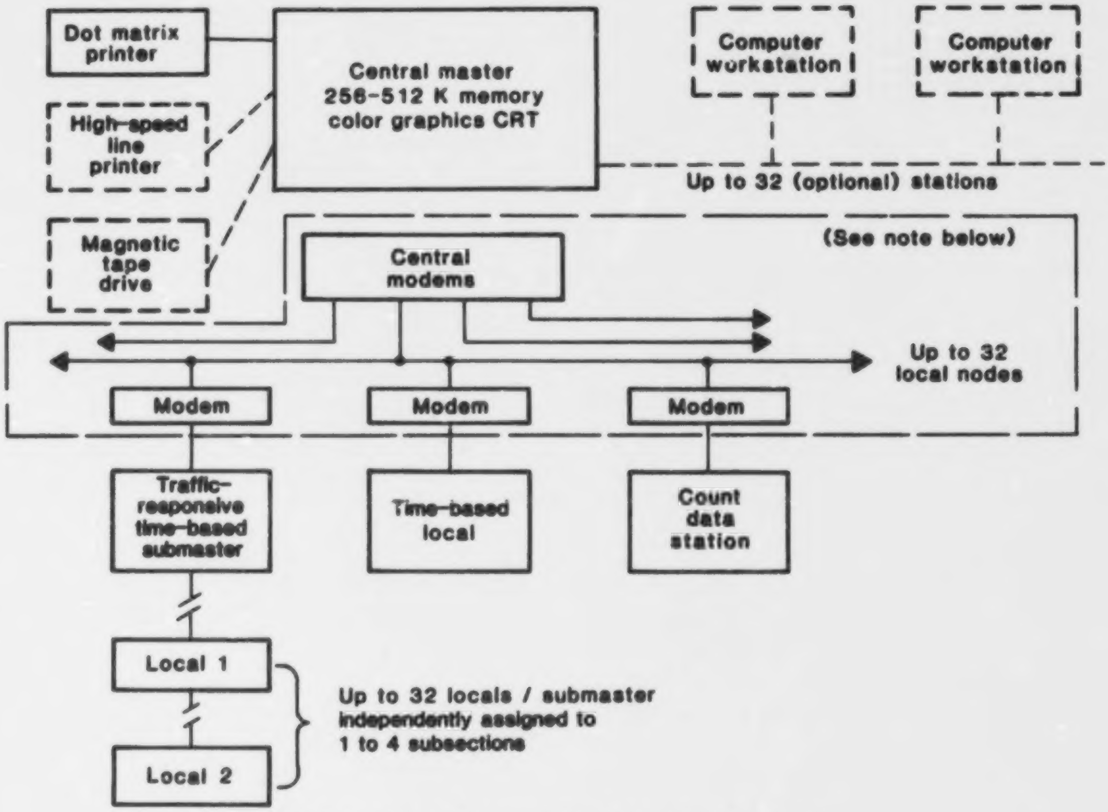
The central facility has the capability of monitoring up to 16 subsections (with up to 512 local nodes/channels).

The submaster(s) are onsite Model 170 controllers units equipped to generate traffic-responsive pattern commands as indicated by sampling detectors strategically placed within the subsystem. The submaster also monitors the operation of local controllers and automatically reports failures to the central computer when malfunctions are detected. The submaster(s) can operate in any of the following modes:

- Traffic-responsive patterns selection based on dynamic traffic conditions.
- Time-of-day/day-of-week preprogrammed pattern selection implemented by time clock.
- Manual pattern selection based on operator command.
- Remote pattern selection based on command from remote master.

Each submaster has the following basic capabilities:

- Four control subsections
- 32 local controllers
- 32 system detectors (8 per intersection, maximum)
- Six coordinated patterns (stored at local intersections), with each consisting of a combination of cycle, offset, and split values. (Additional operations are free and standby.)


Dot matrix printer
Central master 256–512 K memory color graphics CRT
Computer workstation
Computer workstation
High-speed line printer
Up to 32 (optional) stations
Magnetic tape drive
(See note below)
Central modems
Up to 32 local nodes
Modem
Modem
Modem
Traffic-responsive time-based submaster
Time-based local
Count data station
Local 1
Up to 32 locals / submaster independently assigned to 1 to 4 subsections
Local 2

Note: Dedicated (or leased) communications network shown.
Two other options are as follows:
- Autodial, autoanswer central modem for switched telephone network
- RF (microwave) communications network

Figure 7.5. JHK distributed traffic control and surveillance system block diagram

System sensor data forms the basis for all traffic-responsive patterns initiated by the submaster. The traffic-responsive plan selection is based on a comparison of volume-plus-weighted occupancy values calculated for the latest sampling period against operator-set values desired for each control plan (1 of 6), free or standby. The duration of each sampling period is operator-selective, from 1 to 15 min. Traffic-responsive operation has the least priority, and it can be overridden by either TOD/DOW or manual operation (in that priority sequence). Additionally, system sensors provide volume and occupancy data to the central computer via the submaster(s).

The local controllers units are also Model 170 units, consisting of the following:

- Local controller assembly
- Local controller communication interface
- Local controller firmware with system communication and time-based coordination

The local controller receives commands from the submaster and places in effect for its location, 1 of 6 stored timing plans. It also provides local-actuated signal sequence and timing for free or standby operation. Each controller is equipped with communications interface for the reception of submaster commands and the transmission of local intersection status data and system sensor data to the submaster. The local time-base coordination is provided for the implementation of plans on a 10-event TOD/DOW, hour-and-minute schedule. A power failure search feature brings the time-base mode into its proper pattern following a power down/up sequence.

Application. The Distributed Traffic Control System, among other applications, is used for central control of large or small signal networks. The system could be incrementally installed, starting with one or more submaster sections operating in a stand-alone mode, and then adding, as needed, other sections. At some point in time, the central control facility for system supervision and the aforementioned offline computer capabilities could also be added.

Transyt 3800 Closed-Loop System (*7*)

The 3800 is a system designed and marketed by the Transyt Corporation for arterial signal control utilizing NEMA-type local controllers. The closed-loop concept embodies two-way communication, an intelligent microprocessor master unit, intelligent monitors at local intersections, and the ability, through standard dial-up phone line and modems, to monitor and control the system from a central office computer. Figure 7.6 is a block diagram of the system.

Features and Capabilities. Three major elements make up the 3800 system: a central (personal-type) computer, the on-street master, and the local system supervisors/monitors.

The on-street master has the primary task of evaluating traffic conditions and selecting the best system timing pattern. Its software includes a detector analysis program to ensure that the correct pattern for current conditions is implemented. Timing plans are selected on a look-up, pattern-match basis from a library of up to 60 patterns. The pattern selection process includes traffic flow analysis in three areas:

- Volume level of arterial for cycle length
- Directionability of flow for offset
- Ratio of arterial traffic to side street for split selection per intersection.

Individual detectors (24 maximum) are user-assignable to any computational channel in the master, and each may be fractionally or multiple-weighted in calculations as required. Two occupancy and two queue detector inputs are also provided to enhance pattern-selection algorithms. The master continually monitors detectors for proper operation by checking for constant calls, absence of call and erratic output. Failed detectors are automatically deleted from the calculations, and they are restorable if proper operation resumes. Thus, the system operation is primarily traffic-responsive with reversion to TOD backup mode if an insufficient number of detectors remain operable. The master also receives failure and status messages from the local supervisor/monitor units. The messages are time-and-location logged and stored for up to 48 hr. Selected messages (by type) may be programmed for immediate relay to the central computer. The entire message log (24 hr) can be relayed for central printout on demand or supplied automatically at a programmed time. The master tabulates and stores 15-min count and pulse length data from a selected set of 12 detectors for a 24-hr period. Local intersection data from as many as 8 detectors per intersection is available as system configuration dictates. Master-to-local unit communication is maintained via built-in TDM/FSK telemetry, over 2 pairs of voice-grade cable, common to all intersections. Up to 30 locals can be supervised and monitored by each 3800 master unit (*7*).

The central office computer used in the 3800 system is an Apple II, with basic peripherals, two disc drives, and a dot matrix printer. The Apple II computer can be used with as many as nine 3800 master units. The floppy disc drives are used to store timing plans and other system data. The central office computer interconnects to the on-street master over a single phone line, with operation by automatic dialing modems. The master is thus used as an intermediary for data transfer between the central computer and the locals. The only online computer function is to receive and print out (or display on CRT) the failure and system status messages from the master. The computer can be used for other purposes a high percentage of the time. Failure messages from the master are, however, recognized even though the computer may not be in the system mode. Other computer functions include the following:

- Monitor detector volume/occupancy levels
- Monitor actual pattern changes
- Down-load adjusted (or initial) timing plans to local supervisor/monitor units
- Override pattern (selected by master) for any local controller, or set to free
- Place entire system in TOD backup mode
- Select 12 detectors for master counting operation
- Request display or printout of detector data stored at master

All programs used are written in BASIC language (*7*).

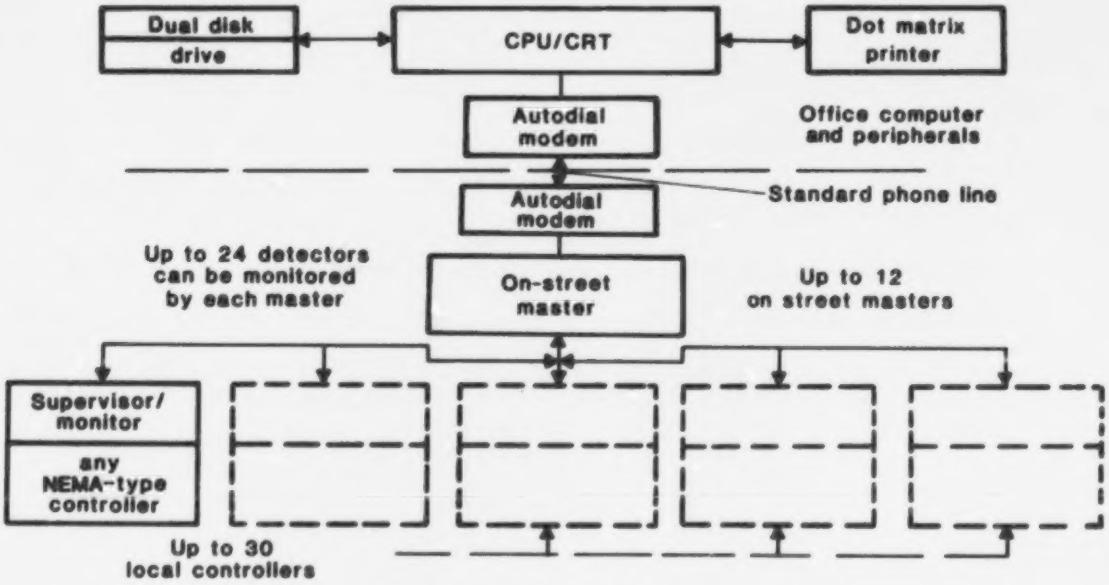

Dual disk
drive
CPU/CRT
Dot matrix
printer
Autodial
modem
Office computer
and peripherals
Standard phone line
Autodial
modem
Up to 24 detectors
can be monitored
by each master
On-street
master
Up to 12
on street masters
Supervisor/
monitor
any
NEMA-type
controller
Up to 30
local controllers

Figure 7.6. Block diagram of TRANSYT 3800 closed-loop system

Source: Reference (*7*)

The local supervisor/monitor unit (LS-3800) will operate any NEMA signal controller through standard hold and force-off inputs. Each LS-3800 has a built-in time-base coordination for use in the backup mode. Any loss of communication or failure of the master unit reverts each local supervisor unit to the state in which selected plans (from the 60 available) are implemented on a TOD basis, while the system coordination is maintained. The system can also be configured to operate only in the time-of-day mode, a state in which the master does not send pattern selection commands, but conveys only time-sync pulses to the LS-3800 units. Supervisor/monitor units also have the following functions:

- Monitors operation of its local controller, conflict monitor, and other selected cabinet functions
- Monitors local's response to master sync commands
- Monitors (through 6 programmable inputs) such conditions as: conflict flash, manual flash, time-clock flash, preemption active, and manual control active
- Notifies master when and if normal local operation resumes
- Transmits system sampling detector data to master (via up to 8 available channels) (*7*)

Application. The 3800 system could be utilized in a small network, but it is probably best suited for linear arterial systems. Its main versatility from the hardware aspect is its ability to supervise NEMA-type controllers, and its apparent ease of expansion. Conceivably, it could be used to control 2 intersecting arterial systems. Controlled arterials need not be located physically near to one another, considering the auto-dialing modem communication setup used.

Econolite KMC-10,000 Master System (*8*)

The KMC-10,000 is a system for arterial signal control designed and marketed by Econolite Control Products. KMC (Econolite) series controllers, of the full-actuated type are required as locals for the system. Two-way communications, intelligent microprocessor master and local controllers, and a central-office, personal-type computer comprise the KMC-10,000 system, as shown in the block diagram of the system in Figure 7.7.

Features and Capabilities. The street master (KMC-10,000) unit has the capacity to command and supervise 24 local intersection controllers (KMC series) and 32 sampling detectors. The master(s) communicates with the intersections and detectors by TDM/FSK telemetry, via voice-grade wire pairs. The system commands

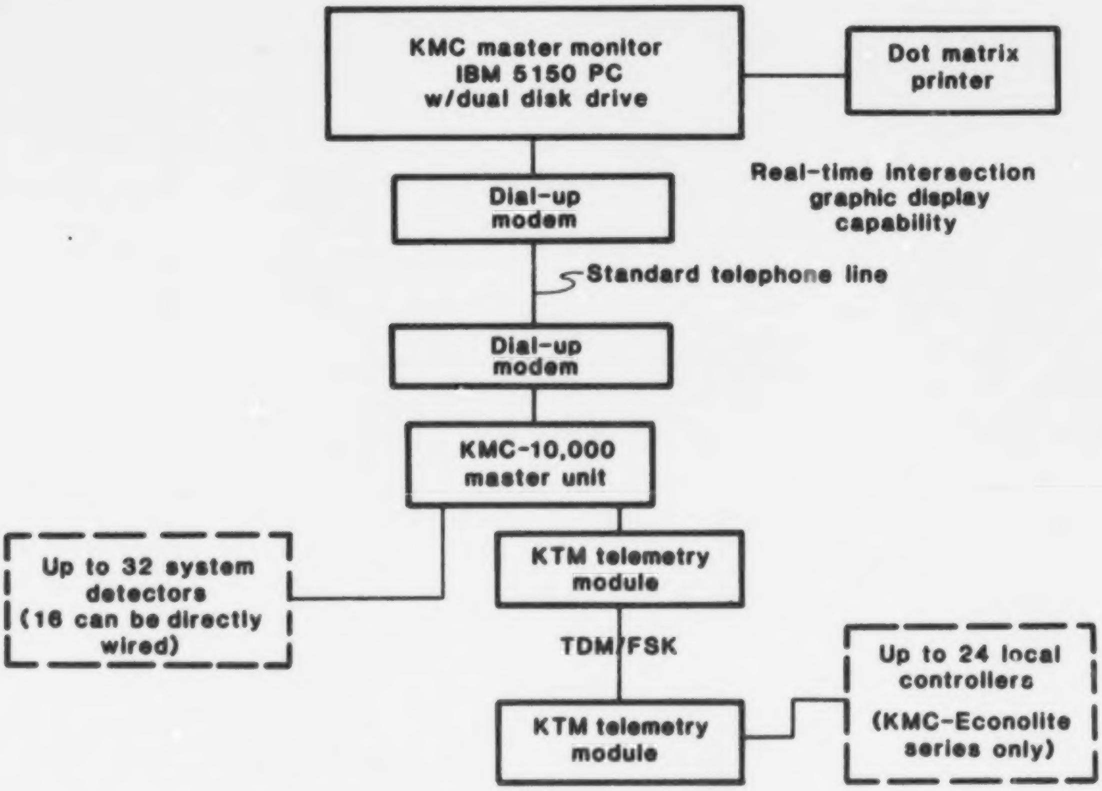

KMC master monitor
IBM 5150 PC
w/dual disk drive
Dot matrix printer
Real-time intersection graphic display capability
Dial-up modem
Standard telephone line
Dial-up modem
KMC-10,000 master unit
Up to 32 system detectors (16 can be directly wired)
KTM telemetry module
TDM/FSK
KTM telemetry module
Up to 24 local controllers
(KMC-Econolite series only)

Figure 7.7. Block diagram of KMC-10,000 incremental master system

Source: Reference (8)

include traffic plans that specify coordination programs of 6 cycle lengths, 5 offsets, 4 splits, and 4 special functions. Both the master and the local controllers are microprocessor-type units, and communications between them is provided by identical microprocessor-based telemetry modules.

The coordination modules utilized in the system will directly accept offset and phase split percentages and other timing plan data via keyboard entry. Unique capabilities for handling local intersection control are provided by the coordination module, including the following:

- Extension of the coordinated phase if overload occurs
- Re-servicing of noncoordinated phases or selection of a special split to clear excessive queue (split selected by monitoring continuous demand from queuing detector)
- Time-base coordination for online or standby operation

Capabilities are provided by the street master to perform diagnostics on system detectors, telemetry, and intersection operation, and to log various failed parameters. The local coordination units perform diagnostics on respective intersection operations, identify various failures, and transmit them to the street master units for logging and/or alarm.

An RS-232 interface is provided in the (street) master for interconnection to the local or remote data terminal, and to the printer and disk drive(s) for data logging of system changes, status reports, and current status updates.

An IBM personal computer is used as a remote data terminal for the system. This computer accesses KMC-

250

10,000 street master(s) via dial-up telephone service. Together with the disk drive and the printer, the functions of the microcomputer in the system include the following:

- Data entry to KMC-10,000 street master(s)
- Logging and event records
- For KMC-10,000 the file management configuration includes the following:
  - Enter all PROM data and save on on disk
  - Download all PROM data
  - Upload all PROM data
- For intersection file management, the procedure is as follows:
  - Enter all configuration PROM for each intersection and save on disk
  - Download selected data to the controller, coordinator module, or time-base coordinator
  - Upload all configuration PROM data
- Intersection graphic display

In addition to the offline system functions listed above, the microcomputer provides computing capability for traffic engineering programs (*8*).

Application. For the KMC-10,000 system, applications include the use of 2 street masters to supervise locals in crossing arterial configuration. Coordinated traffic flow for both subsystems through the common intersection is possible. Each street master will supervise up to 24 intersections. Thus, new subsystems can be added to the system as need grows, and, if desired, the central master computer need not be added until some designated future point. One microcomputer can supervise up to 9 street master units.

Safetran CM1655 System (*3*)

The Safetran CM1655 System utilizes proprietary, identical 16-bit microprocessors as submaster and local controller units. The central master unit employed may optionally be a proprietary unit manufactured by Safetran; or a personal-type minicomputer, another 16-bit microprocessor (identical to the submaster and local controller units), or an intelligent CRT terminal. These optional arrays are shown graphically in Figure 7.8.

Features and Capabilities. If the proprietary type central master is selected for the system, it provides control and supervision of the overall system through synchronous 1200-baud communication links with up to 8 submaster units, each of which supervises communications and control for up to 16 local controller units. Up to 16 sampling detectors may be connected to each local unit for processing through the communications system, thereby giving a total subsystem capacity of 256 detectors. One-half of the 256 sensors can be used for overall subsystem traffic-responsive operation.

Local masters store and select from 10 programmable coordination plans which may be implemented on a traffic-responsive or time-of-week basis. Plans may also be controlled or changed by a system master command or by local manual selection. Each control plan consists of parameters which control the cycle, split and offset of each intersection within the system. All values except cycle length, which is common for all intersections, are independently programmable for each of the 16 intersections.

The basic independent mode of operation is automatic, in which plans are selected on the basis of system volume, occupancy, and flow directionality. TOW commands override automatic operation and manual commands. In addition to the 10 control plans, flash and free operation may be selected by time of day on a systemwide or on an individual intersection basis.

Error-checking routines are used to assure that stored timing plans are valid before being used. Microprocessor operation is monitored for proper program cycling by a watchdog timer. Either a loss of confidence in memory contents or a processor failure places the intersection into flashing operation. Error-checking routines also test for proper detector function. Malfunctioning detectors are automatically removed from system computations, and error messages are transmitted regarding detector failure status.

Timing plans are checked for validity before being transferred from master to local controller when a plan change is required. All local coordination is internal to the controller, and phase plan changes are provided for lead-lag and lagging-turn operation.

Communication system error checking is accomplished with the use of data check sum.

Application. For the Safetran CM1655 System, applications include the incremental conversion of existing sub-systems through replacement of existing controllers and installation of a submaster for stand-along operation. Expansion for the future could then be done by adding sub-systems and eventually building into overall citywide control by central supervision of submasters. A personal-type microcomputer or a more sophisticated unit could optionally be employed in that role.

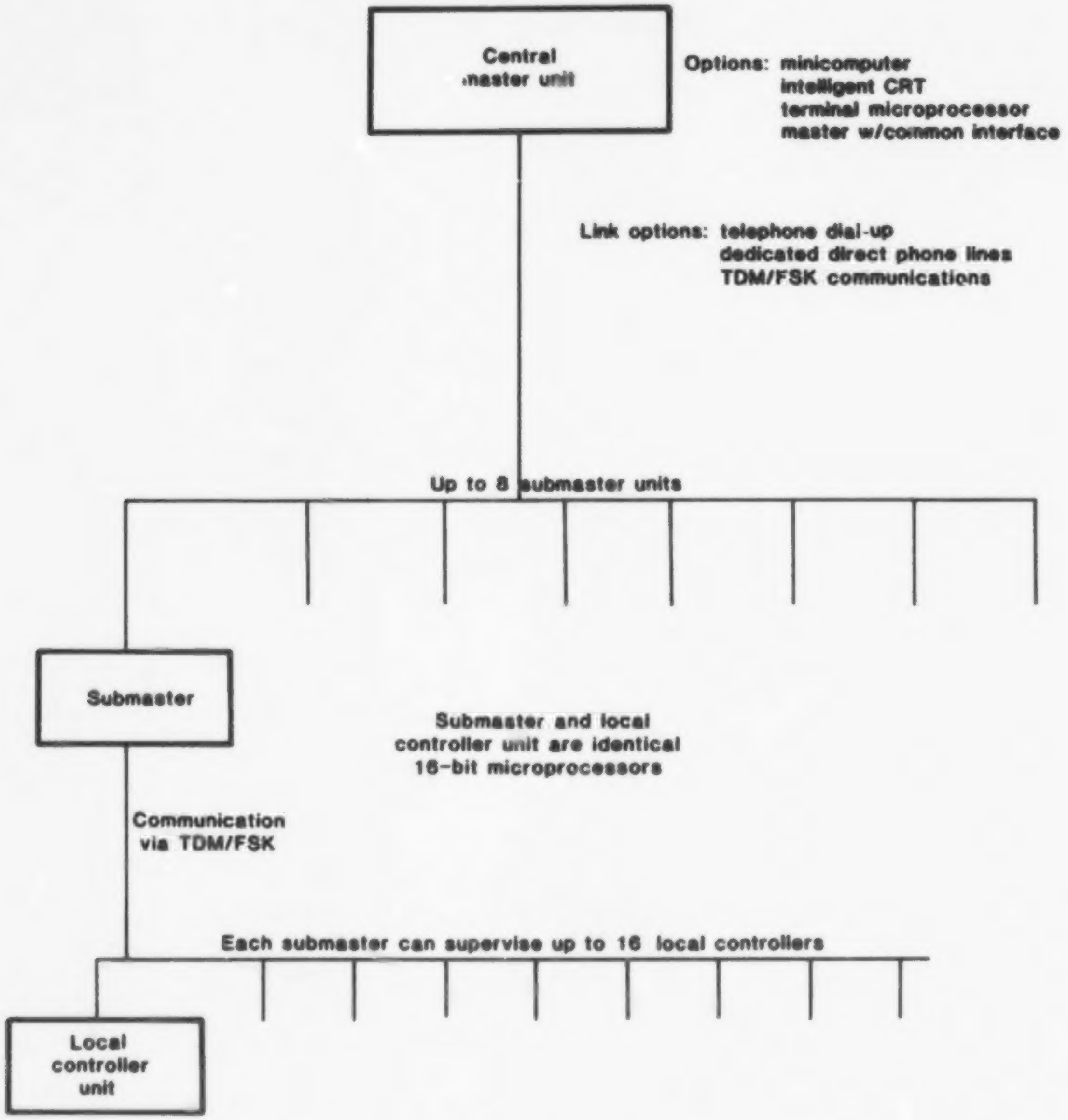

Central
master unit
Options: minicomputer
intelligent CRT
terminal microprocessor
master w/common interface
Link options: telephone dial-up
dedicated direct phone lines
TDM/FSK communications
Up to 8 submaster units
Submaster
Submaster and local
controller unit are identical
16-bit microprocessors
Communication
via TDM/FSK
Each submaster can supervise up to 16 local controllers
Local
controller
unit

Figure 7.8. Safetran CM1655 system block diagram

252

7.5 BASIC COMPUTERIZED SIGNAL SYSTEM (*12*)

The concept for the Basic computerized system was formulated by the Committee on Traffic Control Devices of the Transportation Research Board in a meeting in 1980. Basic was conceived as a stand-alone system capable of malfunction detection, centralized installation of timing plans, and simplified operator's interface. The software capabilities and hardware components normally present in the control-type installation which were deleted in the Basic concept are listed as follows:

- Traffic-responsive operation mode and MOE's
- Critical intersection control via central facility (could be provided at local through use of intelligent microprocessor-type controller)
- System detectors
- System status map

The features and capabilities of the Basic system include the following:

- The central control facility consists of a small mini- or microcomputer with 16K to 32K of memory, disks and disk drive for additional memory storage, and console typewriter or dot matrix printer. With the proper software resident, a Model 170 unit could be utilized at the central facility. An operator interface would be required only periodically for such actions as imposing manual timing plans, changing timing plans, malfunction diagnosis, repair, etc. Timing plans are programmed and stored while the system is online, and then dumped into the computer when it is offline. Fine tuning changes, for a limited number of intersections, can be done while the computer is online, and then stored and dumped into memory during offline conditions. Timing plans cannot, however, be installed or updated online.
- The operator's interface is conceived to be very simple, with menu-driven software a necessity. System staffing, time constraints, personnel turnover, and other related problems encountered in the majority of jurisdictions indicate the need for readily understandable procedures for man-machine relationships.
- Malfunction detection and diagnosis, together with provision of alarms and automated logging — features most traffic engineers consider to be highly useful — are provided in the Basic system.
- Implementation of timing plans is accomplished either by operator manual override or by a TOD, DOW scheduler.
- The communication medium for the system is optional. It could be accomplished by utilizing a two-wire pair, TDM/FSK system in which the central computer would provide system control commands. Dial-up/answer modems and commercial telephone hookup also could be used. This concept for communication would, of course, require the use of an intelligent, microprocessor-type controller (a submaster) to supervise groups of locals. Timing plans would then be down-loaded by the computer to submasters for TOD control of respective groups of local controllers.

It is recognized that many jurisdictions do not find that a sophisticated, full-feature computerized system has suitable application to their needs. By limiting the software capabilities and hardware components of a system the costs can be reduced considerably. By simplifying the system, design, procurement, operation and maintenance become less complicated procedures. The Basic system is not intended to eliminate the selection of more sophisticated signal systems where such systems are appropriate. Rather it is intended to be an alternative tool that can be used to provide traffic performance and fuel conservation benefits achievable with improved traffic control signalization. The Basic system is applicable to large and small networks and arterial systems. Figure 7.9 is a block diagram of the Basic system concept.

It is also recognized that the Basic system concept could be altered so that the end result would be a computerized system with capabilities and features placing it somewhere between the full-blown control concept and the relatively limited, simpler system described above (*12*).

7.6 UTCS SOFTWARE

The term Urban Traffic Control System (UTCS) is used throughout this chapter. UTCS is the designation for a research project established by the Office of Research of the Federal Highway Administration in the early 1970s to provide for computer-supervised control of some 200 intersections in Washington, D.C. The principal objective of the project was to develop software for advanced signal control strategies to improve traffic operations in urban areas. Since much of the experience associated with this project is directly applicable to the development of many of today's systems, the UTCS system is referred to in numerous places within this text.

Strategy development in the research project has been defined in 3 generations, usually referred to as 1-GC, 2-GC, and 3-GC. These traffic control techniques are described as follows:

- First-Generation Control (1-GC) — This generation

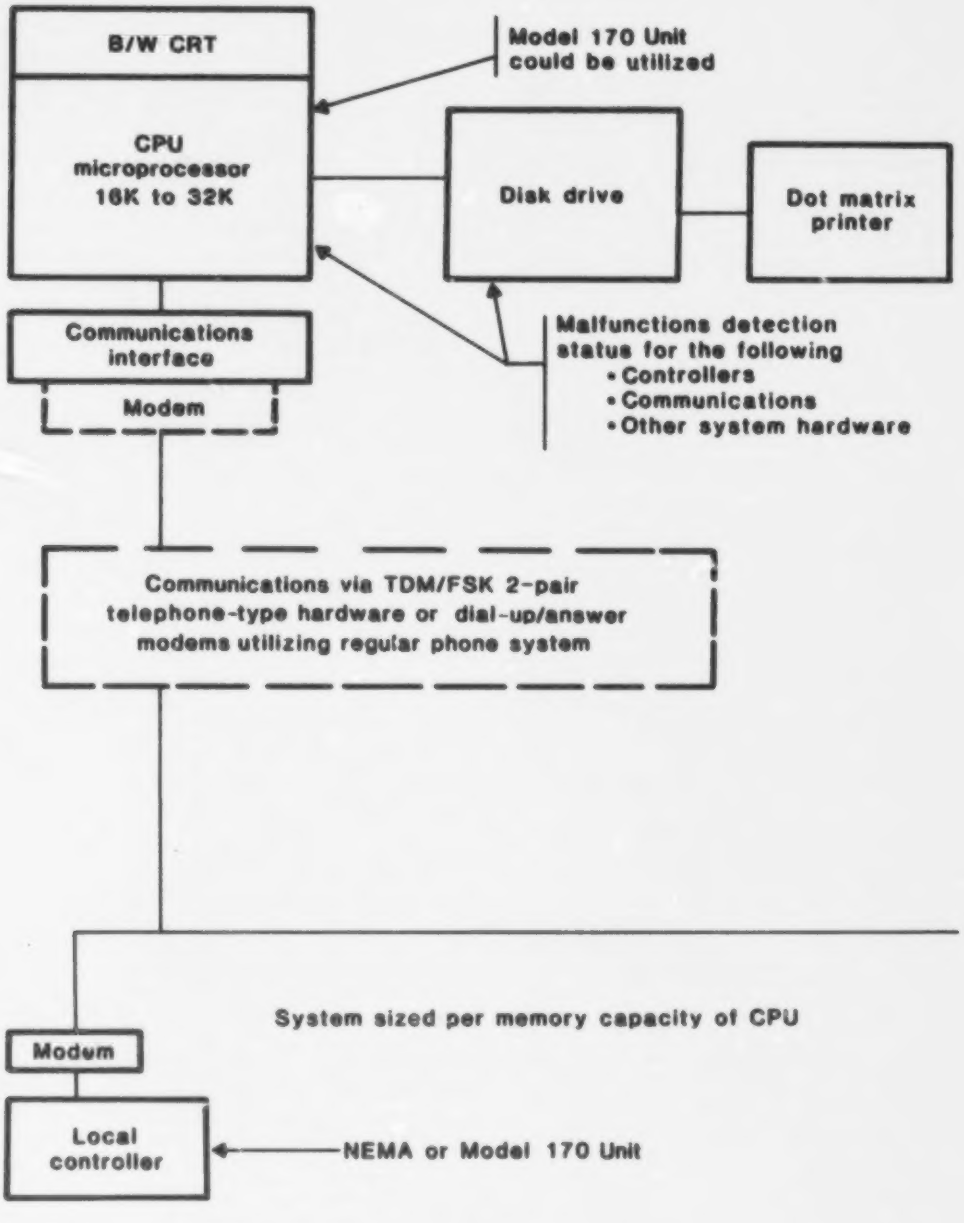

B/W CRT
CPU microprocessor 16K to 32K
Model 170 Unit could be utilized
Disk drive
Dot matrix printer
Communications interface
Modem
Malfunctions detection status for the following
• Controllers
• Communications
• Other system hardware
Communications via TDM/FSK 2-pair telephone-type hardware or dial-up/answer modems utilizing regular phone system
System sized per memory capacity of CPU
Modem
Local controller
NEMA or Model 170 Unit

Figure 7.9. Block diagram of Basic control system

consists of a series of traffic signal timing plans developed offline, and based on historical traffic patterns. Specific plans can be selected via time-of-day, by direct operator manual override, or by matching from the existing storage, a plan that is best suited to recently measured traffic. Timing plans for use in 1-GC can be derived manually, by trial and error, or, most appropriately, in larger complex systems, by utilizing

254

one of the offline computer software models for traffic signal optimization.

- Second-Generation Control (2-GC) — The second generation is an alternate to the stored library of timing plans used in 1-GC software, 2-GC involves the real-time production and implementation of plans through on-line techniques based on surveillance data gathered from vehicle detectors and from predicted traffic volumes. The software also has the capability of dynamically restructuring the network into sections on the basis of real-time traffic conditions. A number of other routines designed to improve flow within the network are contained in 2-GC software.
- Third-Generation Control (3-GC) — The third generation is a significant departure from the 1-GC and 2-GC strategies. This concept is to implement and evaluate a fully traffic-responsive, online control system. To accomplish this, signal timing parameters must be changed continuously in response to real-time measurements of traffic variables. Numerous problems associated with instrumentation and transition-related deficiencies forced the discontinuation of development work on 3-GC, and further work in this area is not currently planned.

The reader is referred to Chapter 3 of this Handbook for a more detailed discussion and comparison of these three strategies.

It is important to determine the magnitude of improvement (or degradation) in traffic operations within a network both before and after the implementation of a computerized control system. Measures of effectiveness (MOE's) were generated for this purpose by the UTCS system, based on the following:

- Volume — The volume is estimated as a simple count of the number of vehicles passing over a detector in a 15-min period. When a link has more than one detector, the volume is determined by a summation of detector estimates divided by the number of detectors.
- Average speed — The average speed is based on the time a vehicle takes to traverse a 6-ft by 6-ft single loop detector. The time is corrected by applying average vehicle length and any detector-bias factors.
- Occupancy — The percent occupancy reflects the proportion of time that a detector is occupied by a vehicle traversing a link.
- Queues — This is a relatively complex measure reflecting average link occupancy rather than simply the length of a standing queue. Multiple (longitudinal) detectors are required per link to obtain this MOE, which is based upon average link occupancy per cycle in a 15-min period.
- Delay — Also a relatively complex measure, delay is calculated as the difference between the time computed, using surveillance data, for a vehicle to traverse the detectorized segment of a link, and a free-flow travel time under uncongested conditions.
- Number of stops — This measure is based on zone count data similar to that used for queue and delay MOE's. A downstream critical arrival time is established based on a standard time-space trajectory (for nonstopping vehicles). Vehicles arriving after the appropriate critical time has elapsed are assumed to have stopped.
- Travel time — This is an estimated measure based on a portion of the delay calculation, and accumulated for all vehicles traversing the link within a 15-min period.

The MOE's outlined above are not intended to duplicate precisely the standard traffic engineering measures of the same names, but they are realistic surrogates for them based on the data generated in the UTCS system. Although they may not exactly duplicate values used in software for current control systems, they do cover most of the types of MOE's usually defined.

Equipment monitoring is also provided in UTCS software, with the following items of equipment being continuously monitored for failure:

- Local controllers
- Vehicle detectors
- Communications
- Central processing unit (CPU)

Devices utilized by the UTCS system to display and communicate information include the following:

- Map display
- Cathode ray tube (CRT) displays
- Teletypewriter
- Line printer
- Control panel

The traffic control panel, which permits operation selection and supervision of the overall traffic surveillance and control system, is divided by function into the following sections:

- System control — This function provides the operator with the capability of placing the controllers in a

255

standby or under computer control either individually, by section, or as a total system. It also provides for selection of operational modes.

- Map control — This function provides the operator with capability of selecting various modes and thresholds for map display.
- Status display — This function provides the operator with the capability of selecting intersection, section or system status CRT displays.
- Malfunction indicators — These indicators are activated when there is a malfunction of any of the major system components such as the CPU, detectors, controllers, or communications.

The original UTCS software was written totally in Assembly language to facilitate experimentation. To reduce the programming required to implement software in other cities and on different brands of computers, the FHWA converted the software to ANSI Fortran and demonstrated it in Washington, D.C., in 1973 (*11*).

First-Generation Extended and Enhanced Software

The FHWA recognized the need to test the UTCS FORTRAN version of the software in a system which had different characteristics than existed in Washington, and one which utilized a state-of-the-art computer. In 1976, a pilot installation was activated in Charlotte, North Carolina, for the implementation of UTCS-extended software (*11*).

The structure of the UTCS-extended software embodies three levels of priority, based on the timing that is required by the programs that execute within them. Figure 7.10 is a block diagram representing the relationship between the executive program (the priority supervisor) and the three priority levels. As shown in Figure 7.10, Priority Levels 1, 2 and 3 operate at interrupt frequencies (in seconds) of 1/32, 1, and greater than 1, respectively. Examples of functions performed by routines at each of the priority levels are shown in the figure. The operation of the executive (or supervisor) is initiated by a clock, external to the computer and software operated, that interrupts the computer every 1/32 sec. Thus, the executive performs the necessary computations to ensure the respective priority levels are serviced appropriately in the hierarchical structure. Both the executive and the Priority Level 1 routines are programmed in Assembly language rather than in FORTRAN. The executive routine is programmed in Assembly language because it contains instructions related to interrupt processing and other detailed computer functions that are not available in ANSI FORTRAN. The Priority Level 1 routines are programmed in Assembly language because of the high rate at which they operate. The high rate requires a highly efficient program structure which can best be accomplished using Assembly language (*4*).

The UTCS-extended software also permits use of a feature available from all minicomputer manufacturers known as overlaying. This feature permits areas of memory to be used to store a number of different computer software segments which are loaded from the disk into the reserved memory area when they are required. When the software segment currently in memory has completed its execution or is interrupted by a higher level, the operating system retrieves the next software segment required and stores it in the same area of memory as the previously used segment. Thus, the original software segment is overwritten (or overlaid) by the first segment. The purpose of this feature is to reduce the total amount of memory required for the execution of a program (*4*).

The overlaid version of the UTCS-extended software is structured in the following manner:

- The executive and the Priority Level 1 routines are resident; that is, they are always in memory and never overlaid but are shared in an area of approximately 22.5K bytes.
- A Priority Level 2 overlay area of approximately 8K bytes is reserved to be shared by all Priority Level 2 routes.
- A Priority Level 3 overlay area of approximately 8.5K bytes is reserved to be shared by all Priority Level 3 routines.
- Additional resident data and programs that are not overlaid include the operating system, background processing, and database storage. The memory requirements for these items are highly variable (*4*).

The FHWA initiated the first-generation UTCS-enhanced software development project in 1977. After several delays, the software was tested on a Honeywell computer in Broward County, Florida, in 1982 and conditionally accepted. The testing has been completed in Birmingham, Alabama, on a Perkin-Elmer computer. The software successfully controlled 246 intersections and 185 detectors in Birmingham (*11*), and in 1984 was accepted by the FHWA.

The UTCS-enhanced software manages and schedules the overall traffic control operation. However, rather than managing the operation of three different priority levels, the Enhanced executive manages 10 different tasks, including the following:

- System startup
- Manager of real-time tasks

256

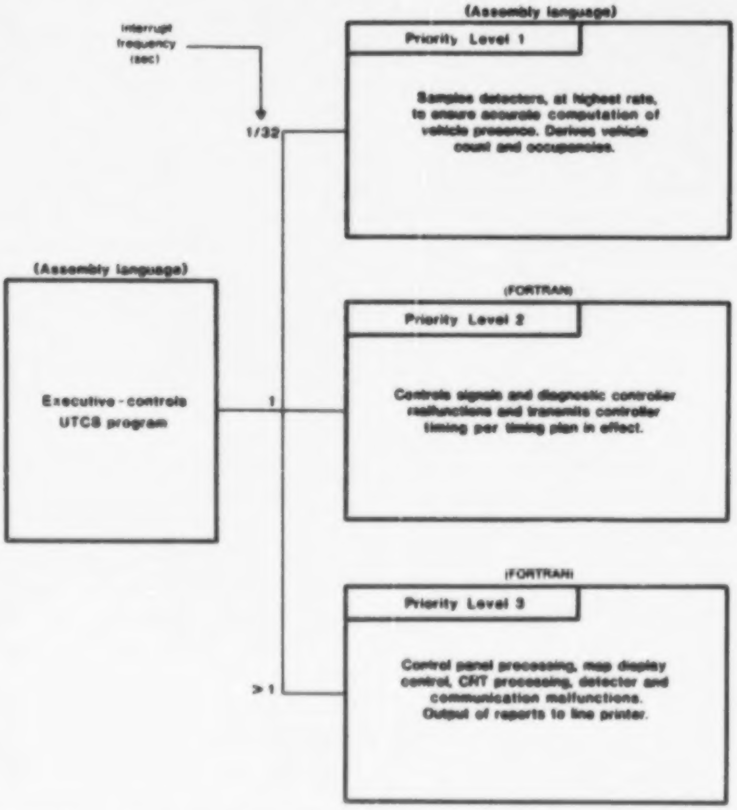

interrupt frequency (sec)
1/32
1
> 1
(Assembly language)
Executive - controls UTCS program
(Assembly language)
Priority Level 1
Samples detectors, at highest rate, to ensure accurate computation of vehicle presence. Derives vehicle count and occupancies.
(FORTRAN)
Priority Level 2
Controls signals and diagnostic controller malfunctions and transmits controller timing per timing plan in effect.
(FORTRAN)
Priority Level 3
Control panel processing, map display control, CRT processing, detector and communication malfunctions. Output of reports to line printer.

Figure 7.10. Urban traffic control system (UTCS) extended software priority levels

Source: Reference (*4*)

- Process TOD, DOW schedule
- Process operator commands
- Process report commands
- Manage data base
- Process traffic-responsive operation
- Log status
- Load/update data
- System shutdown

With the exception of the real-time tasks, each of these tasks is activated by, and loaded into memory under the control of the executive. For this reason, this executive requires more extensive processing capabilities than the UTCS-extended executive (*4*).

While the basic control philosophy of the UTCS-enhanced software is similar to that of the UTCS-extended software, numerous features have been included in this package to provide enhanced control capabilities and increased system flexibility. Some of the differences between the enhanced and extended software packages include:

- The enhanced software offers the capability of scheduling timing plan selection, reports, and operating modes at 1-min resolution. The extended software only offers the capability for prescheduling TOD timing plan selection at a 15-min resolution.
- Up to 10 timing plans can be made available for traffic-responsive selection for a given time of day using the enhanced software. The extended software permits selection from four timing plans. In both

257

cases, the plans that are eligible for selection can be changed for each selection time.

- The enhanced software permits the operator to specify the frequency with which timing plans are selected. The extended software permits selections at 15-min intervals.

- The enhanced software contains a feature known as section locking. This can force a section designated as a slave section to select a timing plan with a cycle length equal to the cycle length of another section designated as the master section. The extended software does not include this feature.

- The enhanced software also offers the capability of controlling actuated controllers with numerous specifications such as phase skipping and variable coordinated phases. The extended software does not include this feature.

- The enhanced software does permit data base modifications while the system is online and operating. For example, timing plans can be modified, controller-to-section assignments can be changed, controller types can be changed, and map-light designations can be altered. Operating parameters such as filter smoothing constants, plan selection frequencies, and various threshold parameters can also be changed. The extended software does have a limited online data base modification capacity.

- The enhanced software can produce many more reports than the extended software. Such reports include system operating status, data base reports, and failure reports and special-purpose reports, including the ability to monitor controller splits on a cycle-by-cycle basis. In addition, reports can be displayed on any device at the direction of the operator, including the line printer, any CRT console, the typewriter console, or the tape drive.

- The enhanced software offers additional equipment monitoring capabilities over those which are available with the extended software. These capabilities include automatic retry after a malfunction has been identified, and the ability to evaluate actuated controller operation by issuing a cycle controller command. The enhanced software reports all controller resynchronization attempts and all errors identified during the system operation.

Although other differences exist between these two software packages, the preceding list describes the more significant ones (*4*).

1½-Generation Control (1½-GC)

A great majority of the systems implemented to date are of the First-Generation (1-GC) type. A 1-GC type, however, does not provide the capability to compute traffic signal timing plans automatically. The user must rely on plans selected from those precalculated and stored within computer memory. The computer selects from these prestored plans for implementation, either in response to measured traffic flow conditions or in response to a predefined TOD/DOW schedule. The effectiveness of the prestored plans can deteriorate because of changes in traffic flow which may occur in the network. Because the effort required to update signal timing plans is labor-intensive, and because most users lack human resources to carry out such efforts, the maximum potential of most 1-GC computerized systems is not being realized (*14*).

1½-Generation Control (1½-GC) adds two principal features to 1-GC as follows:

- It automates the timing plan development task to the maximum extent possible.

- Through automatic recognition of long-term deviation in traffic flows, it detects when the precalculated traffic signal timing plans should be modified (*14*).

Three major functions which the 1½-GC performs are as follows:

- Evaluates the performance of the precalculated signal timing plans implemented by the UTCS 1-GC software and identifies inefficient signal timing plans performance.

- Calculates new timing plans as candidates for replacing those precalculated plans found to result in inefficient performance.

- Provides the capability to select the newly computed timing plans for implementation while the system is operating in the traffic-responsive or TOD/DOW schedule mode (*14*)

The review of newly computed timing plans and implementation decisions remains in the hands of the user in the 1½-GC concept. The user evaluates the suitability of the computed plan based on the MOE's and time-space diagrams. If the resultant outputs are acceptable, the timing plan(s) can be loaded into computer memory for future use. A high level of detectorization, equivalent to that envisioned for UTCS 2-GC, must be present in a system if the UTCS 1½-GC concept is to be effective.

7.7 NETWORK CONTROL SYSTEM MASTERS

To describe the role of the master controller in larger network systems adequately, one must include the other hardware subsystems which, taken together, comprise the entire system. In larger network control systems, the master unit is more appropriately referred to as the computer or central processing unit (CPU). The total functions of the CPU embrace much more than the control supervision of the system.

To illustrate the interaction of the various subsystems, a block diagram for a typical system is shown in Figure 7.11. Each box in the diagram represents subsystem hardware, with the arrows indicating the directions of information flow among them.

The hardware subsystems are used to perform different functions, depending upon the information being passed between them. The basic functions of a traffic control system are as follows:

- Control — The most critical function of the system begins with the master or CPU, which transmits commands to the local signal controllers, where the transmitted information is, in turn, converted to the proper lamp-switching activity at respective intersections. Traffic movement in response to lamp-switching is then measured by the system sampling detectors.
- Surveillance — The next function, begins with the transmission of converted detector data to the CPU via the communications system. Besides using this data for determination of timing plan usage in the traffic-responsive mode, the CPU may also display it via through CRT, wall map and/or printers. Surveillance, therefore, has a dual purpose: control functions and system monitoring.
- Malfunction detection — This function constitutes the ability of the CPU to analyze information transmitted from the various subsystems, and to determine whether or not each is operating properly, thus enabling the rapid detection of equipment failures.
- Operator interfacing — This function provides the means by which humans interact with the system. Computer displays, such as wall maps, supply system output information to the operator who can, in turn, input to the system through control panel or keyboard. A CRT with keyboard is an example of input and output capabilities combined in a single device.

In order to carry out the functions listed, the CPU must either originate required data from its memory and/or process and display data received from other system components. Some of the specific system functions which involve CPU memory and processing actions are as follows:

- Control — Oriented to a timing plan selected from memory, the CPU provides the following:
  - ☐ Section configuration

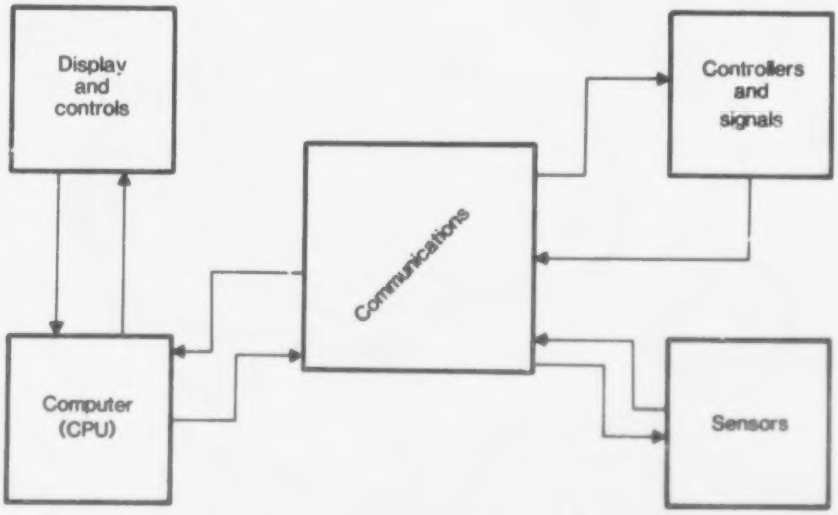


Figure 7.11. Block diagram of a typical traffic control system

Source: Reference (*3*)

  - Signal timing, including cycle lengths, offsets, splits, phase sequence, fixed-interval timing, yield and force-off points, etc.
  - Transition parameters, for orderly movement between timing plans
  - Designation of certain locations for CIC control
  - Designation and sequence procedures for emergency vehicle preemption routes
- Surveillance — oriented to receiving and processing data from detectors installed throughout the system, the CPU provides the following:
  - Sampling of detector data to produce and display measures of effectiveness (MOE)
  - Selection of appropriate timing plan based on processor detector data (traffic-responsive mode)
- Malfunction detection — oriented to monitoring-type data received from other system components, and through its own internal operational check system, the CPU provides the following:
  - Controller unit malfunction indication — corrective measures commenced; if not successful, the failed controller status is displayed and logged
  - Detector malfunction indication — Resulting from vehicle presence measured in excess of specified time, or when counts over a given detector exceed a specified threshold
  - Communication malfunction — Usually derived from turnaround test of accuracy of transmitted data
  - Computer malfunction — Self-analysis by testing the results of the performance of a sequence of computations that exercise the CPU logic
- Operator interface — Oriented to the interaction between the operator and the control system, the CPU provides the following:
  - Input access that permits the operator to communicate with the system
  - System status information to the operator via CRT, color CRT, wall map, control panel, and line printer or teleprinter
  - A means for logging all operational and archival data via line printer, teleprinter, and magnetic disc or tape

The functions of the CPU vary with the degree of complexity of any given traffic control system. Regardless of the size or capabilities of the system, however, the CPU and its accompanying software constitute the heart of the system, on which the other components are dependent.

Large network control systems currently in operation have been assembled around a variety of control concepts. Some systems, even though designed and supplied by the same vendor, are distinctly different in their software and in their overall control strategies.

Custom-Designed Systems

This subsection provides a brief comparison of the salient features of a number of custom-designed traffic control systems offered in the United States for the computer control of larger networks. The systems are considered to be custom-designed principally because they are flexible from the standpoint of operational and communications software and in their system hardware components.

Basically, the systems can usually be adapted by the manufacturer or supplier to satisfy user-derived specifications for the installation of a control system. Typically, the specifications might contain a few unique or special features not found in the standard control and/or system hardware, but with modification, the supplier can accommodate the user's needs.

Table 7.1 lists several custom-designed systems and summarizes the principal features of each. The systems presented are typical base-line installations, and some may have been upgraded or altered by supplier or user to acquire additional control features or to accommodate system expansion.

Package-Type Systems

The systems presented in this subsection are considered to be package-type because of unique and distinctive features in their control software and system hardware components which make them virtually inflexible. These include several traffic signal systems offered in the United States for computer control of large networks. These systems are not, in a broad sense, adaptable for use in applications which require specific functions (not in the package), or in which existing hardware, namely local controller units, are to be incorporated in a proposed system. The uniqueness of the systems in no way detracts from their control capabilities, and the description made is intended only to apprise the reader and potential user that there are basic conceptual differences.

In Table 7.2, the principal features of the package-type systems are summarized.

Table 7.1. Principal features of custom-designed systems

	Computran ATCS and ATCS-II	Computran CTCS and CTCS II	Computran UTCS	Eagle COMTRAC COMTRAC II	Multisonics VMS 220	Sperry SRT	Sperry UTCS
System master[a]	Interdata 70 Perkin-Elmer 8/16	Modcomp II Modcomp 7835	Perkin-Elmer 7/32	Data General Nova	Multisonics 808A	Perkin-Elmer 7/32,332d	Perkin-Elmer and Modcomp
Maximum number of intersections controlled	80 300	1000 300	b	500 500	256	500	500
Maximum number of sections for control	16 31	50 40	b	50 50	100	40	40
Local controller types	Pretimed NEMA-actuated	Pretimed NEMA-actuated	Pretimed NEMA-actuated	Pretimed NEMA-actuated	Pretimed NEMA-actuated	Pretimed NEMA-actuated	
Number of timing plans available	24 65	24 31	b	7 7	512	b	b
Methods of controlling signal timing							
- Manual	X	X	X	X	X	X	X
- TOD/DOW	X	X	X	X	X	X	X
- TRSP	X	X	X	X	X	X	X
Maximum number of detectors used	128 300	1000 350	b	500 500	2048	600	540
Surveillance measures used for control							
- Volume	X	X	X	X	X	X	X
- Occupancy	X	X	X	X			
- Density	X						
- Speed					X		
Traffic-responsive operation[c]							
- Plan selection	X	X	X		X	X	X
- Plan construction		X			X		X
Provision for critical intersection control	X	X	X	X[d]	X	X	X
Provision for online updating of data base	X	X	X	X	X	X	X

[a] Denotes model of computer used

[b] Not specified in manufacturer's documentation

[c] *Plan selection* denotes selection from stored timing plan library, i.e., cycle length, split, offset
Plan construction denotes individual selection from stored values of cycle length, split, offset
Plan generation denotes the online computation of at least one of cycle length, offset, split

[d] CIC not available in COMTRAC II version

261

Table 7.2. Principal features of package-type systems

	Computran TRCS	CSE[a] T-100	CSE[a] T-100	LFE[a] 5000 U
System master[b]	Interdata 8/16E	c	Modcomp IV	DEC PDPII/35
Maximum number of intersections controlled	110	40	850	128
Maximum number of sections for control	7	10	c	8
Local controller types	Pretimed (oriented)	Pretimed NEMA-actuated	Pretimed NEMA-actuated	LFE 118B (oriented)
Number of timing plans available	c	c	c	15
Method of controlling signal timing				
- Manual	X	X	X	X
- TOD/DOW	X	X	X	X
- TRSP	X	X	X	X
Maximum number of detectors used	150	304	1700	128
Surveillance measures used for control				
- Volume	X	X	X	X
- Occupancy	X	X	X	X
- Density	X			
- Speed				X
Traffic-responsive operation[d]				
- Plan selection	X	X	X	X
- Plan construction	X	X	X	
- Plan generation				
Provision for online data base updating	X	X	X	X[e]

[a] CSE - Computer Systems Engineering
LFE - Laboratory for Electronics

[b] Denotes model of computer used

[c] Not specified in manufacturer's documentation

[d] *Plan selection* denotes selection from stored timing plan library, i.e., cycle length, split, offset
Plan construction denotes individual selection from stored values of cycle length, split, offset
Plan generation denotes the online computation of at least one of cycle length, offset, split

[e] Limited changes only, according to manufacturer's documentation

Source: Reference (*3*)

7.8 OPTIONAL CONTROL AND OTHER SOFTWARE FEATURES

Control, which has a direct effect on traffic flow, is probably the most important system function. As previously discussed in this chapter, control begins with the selection and/or computation of signal timing plans. The selected plan data is sent to controllers via the communication system in the form of signal advance pulses and/or yield and force-off pulses for control of signal timing at the local intersections. In a system with a down-loading capability, the timing plans are sent to submaster units for implementation in respective subsystems.

The surveillance subsystem, in turn, measures vehicle flow and sends information back to the computer for indirect or direct selection of new timing plans. The basic ingredient, therefore, is the particular control strategy selected such as first-generation time-of-day, or first-generation traffic-responsive.

The primary features of the control strategies were previously discussed, but a number of the optional, secondary functions related to control, which must also be considered during the development of a control system, are presented and discussed in this section.

Preemption (*4*)

Signal preemption, which can be defined as any technique which overrides normal signal sequence and timing, can be performed for any one of a variety of reasons, including:

- Reduced delay for emergency vehicles and conflicts between emergency vehicles and other traffic
- Modification of phasing and or green allocation because of a temporary roadway obstruction, such as an occupied railroad grade crossing or an open drawbridge
- Reduced delay to transit or other high-occupancy vehicles.

In a computerized traffic control system, the preemption of a signalized intersection may be accomplished using several techniques, including the following:

- Vehicle presence is detected on the selected approach(es) to the intersection, and local intersection logic issued to override existing signal timing. An example of this technique is the use of optical-type or radio transmitters mounted on designated vehicles with receivers installed at the intersection. This method includes transmission of preempt status back to the computer so that the preemption will not be identified as an equipment malfunction. Typically, when the preempt condition ends, the local controller returns to standby status for subsequent computer pickup. This technique is usually used for emergency vehicles since its operation is not dependent upon computer online status.
- Vehicle detection is transmitted to the computer via local electronics and the communication system and the computer, in turn, determines the modifications in signal timing required to serve the preemption. The technique is usually utilized for noncritical preempts, such as those for transit vehicles or to favor certain traffic approaches at a location near a grade crossing or drawbridge. Obviously, proper preemption function in this technique is computer-operation dependent.
- Preemption is initiated by a switch closure at a firehouse or other emergency vehicle housing facility. Closure causes the preempting, in sequence, of a group of signals along a preplanned route or routes. Response to switch closure can be handled either directly by local controllers or be routed for computer control of the fire route preemption. If the computer/communications system is utilized for this technique, particular emphasis must be given to reliability and maintenance of these components of the system (*4*).

The use of preemption in the system must involve design that is responsive to considerations of vehicle and pedestrian safety and the degree of response necessary to the condition. In some systems, the system master is automatically informed of the preempt condition, and such operations are logged (*4*).

Unattended System Operation (*4*)

Depending upon the overall control system concept, consideration should be given during the design stage for hardware and software features that permit unattended system operation. Such operation requires that the system operate safely and effectively when left alone for periods of several days. Features required include the following:

- Automatic power failure detection and restart
- Prescheduling of timing plans and other control functions
- Detailed exception reporting of signal operation
- Automatic retry of failed equipment

Automatic power failure detection is a feature that should be included in all systems. This permits the central processor to detect an impending power failure and to shut itself down before serious damage or loss of data occurs. Automatic restart and rebooting of the system requires a battery-operated clock connected to the CPU. When power-up recurs, a special program reloads the central memory, initializes the system, and the CPU begins operating. The clock thus provides the CPU with the correct TOD reference.

Equipment Malfunction Detection and Failure Reporting (*4*)

The computer should continuously check all equipment in system to ensure its operability. Different approaches are used for the analysis of each subsystem's operation.

Signal controller unit failures are identified by comparing the current signal indication with the interval that the computer expects the local unit to be displaying. In many cases, only Phase 1 (major street) green is returned; however, when full-actuated controllers with phase-skipping capability are included, additional status on phases must be sent to the master. The return of only a single phase green will simplify the communication design. When a failed controller is identified, the computer places the controller in the standby mode, displays the failure to the operator, and logs it to the appropriate system report. Upon input by the operator of the repaired status for the controller failures, the auto pickup process is initiated to bring the controller to online operation.

Detector malfunctions are indicated if a vehicle presence is measured for more than the normal detector time-out period for a parked vehicle, or if the vehicle count over a given time period exceeds a threshold value. Typical threshold values are 32 vehicles per cycle, but they can be operator-selected. In some systems, threshold values are TOD, data base variables.

The monitoring of the communications subsystem depends on the type of subsystem used. A common test of the subsystem is the absence of a detector count for an excessive period of time. A communications cable failure could be identified by large numbers of apparent equipment failures sharing a line. Malfunction detection is also available in some systems by testing the data transmitted (or received) for accuracy. If the test is frequently failed, a malfunction is displayed.

The computer itself requires the most careful analysis for possible malfunction. Self-analysis is performed by the computer, and it includes the performance of a sequence of computations that exercise the computer logic and test the results against prestored answers. A second test requires the computer to read data out of every memory location, change its value, restore it, and then read it out of that location again to check for the correct value. Memory operability is thus evaluated. A final test that ensures that the computer has not completely failed or is in closed-loop operation is sending a toggle pulse to an external device known as a watchdog timer. The toggle pulse is sent by the computer to the timer at intervals of 1-2 sec. If a pulse is not received, the timer initiates an alarm. If the watchdog timer is triggered, the communications system is disabled automatically as a safeguard against transmission of erroneous information to the local controllers.

Failure reporting can be done visually, via a CRT or a control panel, and/or by logging via high-speed printer, teleprinter, disk or magnetic tape. Remote failure reporting provides the system with the capability for reporting malfunctions (at a site other than the control center) where personnel could monitor its operation, such as at a maintenance facility or police dispatch center. Only problems which could be corrected by those monitoring conditions, however, should be sent to respective remote locations.

Backup Techniques (4)

Motorists using the street system depend upon the reliable operation of the signal system. The design of a computerized traffic signal system must give careful consideration to the effect of component failure on system operation. A backup mode must be provided to ensure that the signals continue to operate in case of computer and/or communications failure.

Many types of backup with varying degrees of complexity are possible. The purchase of two of everything — computers, controllers, and communications equipment is the obvious form of backup. Practically speaking, however, it is not feasible to provide this kind of backup and stay within a reasonable cost frame for the system.

Feasible backup techniques must, therefore, be centered around the controller assembly and communications subsystems. Two basic methods are as follows:

- Use of a standby master unit (time-clock or smart microprocessor) and additional communication links for coordinated control of groups of local controllers.
- Use of time-base coordinators (TBC) in each local controller assembly. TBC's were discussed previously in this chapter. Some local controller units can be equipped with modular TBC units by the manufacturer.

Controller Down-Loading and Up-Loading (4)

The flexibility of the microprocessor-based controller permits the use of different computer control concepts. New designs are being developed and installed that make use of a technique known as down-loading.

Online down-loading requires an entire timing plan to be loaded from the central computer to the controller. Data is transmitted to the controller using the same communications channels as those used for the advance and hold-on-line signals. This data is checked for transmission errors and stored in the microprocessor memory. Although there are a number of different techniques for online down-loading, the two basic ones are as follows:

- A number of timing plans are developed, assigned numbers, and stored at each controller. The plan to be implemented is selected by transmission of the plan number from the computer. No additional transmissions are required until the next plan change, but the computer continues to monitor local operation to ensure proper coordination. The disadvantage to this technique is that it is difficult to make operator-requested split or offset changes to current plan in effect.

- All signal timing plan values (cycle length, interval timing, offset, etc.) are transmitted from the computer to the controller. Again, this data is transmitted only when a timing plan change is made. The disadvantage to this technique is that substantial data loads are placed on the communication system when a sectionwide plan change is implemented. Other data transmission activities must be suspended to provide for a plan change in a reasonable time period.

In spite of the disadvantages noted, these techniques offer the significant advantage of being less vulnerable to intermittent interference on communications lines. The down-loading approach, with its capability of error checking and retransmission of data, prevents system disruptions in the presence of interference.

Some of the microprocessor-based controller units currently in use require that all operating parameters, including backup plans, be entered into the controller using a numerical keyboard on the front of the controller. This keyboard operates in the same manner as a hand calculator. The loading of timing plans for backup timing purposes, as well as the additional data required for the controller's operation, may require entry of more than 100 parameter values, a process that is time-consuming and subject to error. The capabilities of the central computer and the microprocessor offer an alternative to the use of the keyboard for entering this data into the controller.

A technique which has been developed to take advantage of these capabilities is known as offline down-loading. A duplicate of the controller's data base is stored in the computer and transmitted to the controller on command from the computer operator. When this data is being transmitted, all other controllers sharing the same communications line must be in the standby mode (not under computer control) to provide the full capability of the communications medium to the exchange of data between the computer and the controller. Each data item transmitted to the controller is then retransmitted back to the computer to ensure that the proper value has been received. If an error has occurred, the computer repeats its transmission of the data to the controller.

This technique is only applicable to smart microprocessor controller units that are designed to accept and store the data. However, it can be used with any of the online control techniques including transmission of advance pulses, force-off pulses, or downline-loading of timing data.

Controller up-loading is the process by which timing plan(s) resident in the microprocessor controller are transmitted to the central computer for inspection and/or modification. The process also could be considered a backup system in the unlikely situation that whereby controller timing plans in disk storage at the control center were inadvertently erased or destroyed.

Memory Overlay and Background Data Processing

Some signal system software designs permit the use of a feature available from all minicomputer manufacturers known as overlaying. This feature permits areas of memory to be used to store a number of different computer software segments which are loaded from the disk into the reserved memory area when they are required for operation. When the software segment that is currently in memory has completed its execution, the operating system retrieves the next software segment that is required (from the disk), and stores it in the same area of memory in which the previously executed segment had been stored. Thus, the original software segment is overwritten (or overlaid) by the next segment required for continued operation. The purpose of this feature is to reduce the total amount of memory space required for program executions (system operation) (*4*).

Many stored data base parameters can be initiated or modified through background processing. Provided sufficient computer memory is available, the following types of programs and routines can be processed in background:

- Traffic data analysis
- Traffic control device inventories
- Traffic engineering analyses, including signal progression programs and traffic simulation models, such as NETSIM, TRANSYT, PASSER, etc.

7.9 CONTROL CENTER FEATURES

The use of digital computers for central control requires a considerable amount of interior space for a control center. As a minimum, adequate space should be provided to serve each of the following functions:

- Computer and peripheral devices
- Display devices (system map(s))
- Communications equipment
- Offices

- Maintenance room

The main computer floor usually is a separate room where temperature and humidity can be closely maintained at desired levels. The floor of the room is usually raised so that space is provided beneath for interconnection of various components. To minimize cable lengths for interconnection, it is often desirable to locate display and communication facilities in, or adjacent to, the computer room.

The following describes devices, other than the CPU, frequently used at the central site to support system operation. Such devices include both standard computer peripherals and special-purpose devices for operation of a traffic control system usually located in the computer room (*4*).

- Wall map — Provides overview information related to the system operation. Although it functions as a public information tool, it also is useful in system installation, testing, trouble-shooting, and maintenance. When properly designed, the map tells the operator at a glance whether all controllers are online or whether a group of controller failures is geographically concentrated, indicating a communications failure. Intersection-oriented indicators on the map include online/offline, failed/operating, CIC/not CIC, and coordinated phase green. Link indicators show whether any MOE has exceeded the operator-selected threshold and detector failures.
- Graphic CRT display — Provides information similar to that presented by the map display, and additionally single intersections are graphically displayed showing dynamic status of signal indications, detectors, position of control within the cycle frame and approximately geometric layout of the intersection.
- CRT console — Provides display of virtually any aspect of the control system. The associated keyboard provides a means of entering commands and data. The keyboard can be used either in place of the control panel or as a supplement to it. Prompts for simplifying system input commands can be displayed on the CRT in a menu-driven type operating system.
- Teleprinter — Sometimes referred to as an online typewriter, the teleprinter offers many of the same capabilities of the CRT console. It incorporates both a keyboard and hardcopy display. In addition to being used to support the traffic engineering displays and controls, the teleprinter is used to communicate with the basic computer system for the starting up of the system and the initial loading of programs. It also displays flow data, display status, and equipment malfunctions, and accepts control inputs through its keyboard. It is also often used to control offline operations. Current trends tend to substitute a CRT/keyboard and printer for this device.
- Control panel — A device that offers the operator easy control of the system through pushbutton switches designated for specific system functions. Its design should provide ready access to a set of functions critical to system operation (such as emergency shutdown), and those functions frequently used (such as map display requests). The proper design of the control panel should include the following physical features:
  - ☐ Rows of buttons should be arranged in logical sequence of decisions.
  - ☐ Buttons should be mechanically interlocked to prevent entries which are simultaneously invalid or illegal.
  - ☐ When a button has been depressed, it should remain illuminated until data is entered or change is made.
  - ☐ Transparent protective plastic covers should be provided for critical action buttons, such as the system shutdown, to prevent accidental activation.
  - ☐ Input to the computer should require the activation of the enter pushbutton as a followup to input selection. This allows an operator review of any input request before action is actually taken.
- Line printer — A standard computer peripheral that is used to produce large volumes of printed hardcopy output which should include the following:
  - ☐ Summaries of flow data (volume, occupancy, speed, etc.) from system and/or count station detectors.
  - ☐ Descriptions of control status and failures.
  - ☐ Offline operations, which can often produce large amounts of data that are better suited to higher speed line printers.

Significant differences exist between printing techniques and characteristics, including the way characters are produced on the paper, the number of characters per print line, the speed at which the printer operates, and a wide range of costs reflecting respective service ability and reliability. Since printer costs increase rapidly as print speed increases, the requirements for these devices should be carefully reviewed prior to selection.

- Hard disks and drive — Used as the primary form of peripheral storage for timing plans and software.

Table 7.3. Summary of available public domain software

Software Designation	Available From	Control Application	Operation Description
FACTS[a] System	Texas Department of Highways and Public Transportation	Arterial and Small Network	Supervision of series of NEMA or pretimed controllers by seperately housed CPU. Software was derived from UTCS version expanded to accommodate diamond interchanges. Surveillance and monitoring included.
BASYS[b]	California Department of Transportation (Caltrans)	Arterial System	Model 170 controller units are used as master and/or local controllers. BAM and BALI software used for master and local, respectively. Flexibility for supervision of a variety of local controller types.
EDIPS[c]	Caltrans (After 1985)	Arterial and Network System	Distributive and intelligent control system which utilizes Model 170 controller units throughout. CPU consists of twin Model 170 units. Three control levels: (a) Level 2-area control (system-master), (b) Level 1-supervisor control, and (c) local intersection control.
UTCS First-Generation FORTRAN IV Extended Version	Federal Highway Administration	Computerized Traffic Control System	(Refer to description in previous subsection)
UTCS[d] First-Generation Enhanced Version	Federal Highway Administration	Computerized Traffic Control System	(Refer to description in previous subsection)

[a] Flexible Advanced Computer Traffic Signal System

[b] Basic Arterial System

[c] Eureka Distributive Intelligent Progression System

[d] Conditionally accepted in Broward County, Florida, in 1982, with final documentation available in late 1984

Source: Reference (*3*)

Because of its ability to access data quickly and accurately, magnetic disk storage represents an attractive price and performance balance between a low-cost tape storage system and much more expensive central computer memory. Several types of disk storage are available including fixed disks that are permanently attached to the drive, and a removable disk pack that can be interchanged. More recently, hard disk drive installations incorporate a combination unit with one fixed disk and one removable disk pack. Thus, data least subject to change resides on the fixed disk.

- Floppy disks and drive — A low-cost form of data storage that relies on the use of a storage medium that is shaped like a small hard disk platter, but is flexible, and in operation relies on centrifugal force to keep its shape. The floppy disk is not as reliable as a rigid (hard) disk system and should never be used for continuous online operation. Its principal operation should be for maintaining historical files of timing plans, new software that is under development, diagnostic maintenance software, or backup for system software.
- Tape drives — Used for storing large quantities of operating data in a compact form that permits later processing primary use is for storage of the large quantities of traffic flow data that can be produced over the life of the system. Magnetic tapes have a much slower access rate than disks, but similar information is oftentimes stored on them in traffic control applications. It is popular in many systems to utilize magnetic tape for backup storage of timing plans for historical and legal reference.

7.10 SOFTWARE AVAILABILITY

Private Sector

Suppliers of computerized signal systems have developed application software using a variety of different structures. Many of the systems now in use incorporate software which is an expanded version of the UTCS First-Generation Extended Version package. The vendor has simply utilized public domain software and added particular custom features and capabilities to it to satisfy the operational requirements contained in respective specifications written for individual traffic control systems. Some of the applications software now in use is structured quite differently from the UTCS concept. In some cases the supplier approaches the control strategy differently because he feels that his system control package need not copy UTCS software, but should have an originality factor built into it. In other cases, specifications are written which make it difficult for the vendor to add to or modify the UTCS software concept and still make his product competitive. He then approaches the problem from an entirely different angle.

The potential system user may acquire a control system which utilizes application software developed in the private sector in one of two ways:

- By approaching selected suppliers or vendors of control systems and obtaining detailed information and specifications for packaged type systems offered. The use of the word "packaged" does not necessarily preclude some minor modification to the system by the vendor, as requested by the user. The user may, in this manner, find a system which will satisfy particular control needs.
- By compiling specifications for a control system which embody desired functional requirements, the user may then produce the documents or may seek the expertise of a consulting firm experienced in the field. The specification stage probably should be preceded by a feasibility study to ascertain the specific system needs. In using this procurement method, the user has the advantage of obtaining a customized system which will have the features and capabilities tailored to his uses.

Public Domain

The potential system-user has the option of utilizing applications software that is public domain. Software in this status is unprotected by copyright or other use restrictions, and full documentation is available so that it can be implemented in control systems by anyone desiring to do so.

Some of the reasons users may chose to utilize software in public domain include the following:

- A jurisdiction knows in advance what system capabilities to expect.
- The software has been in use in several applications.
- The development of the software (on their system) will be avoided, except in cases where the private sector has developed a standard package.
- The source code usually will be written in a familiar language such as FORTRAN, and full documentation will accompany the program, allowing desired modifications.

Table 7.3 is a summary of the public domain software previously discussed in this chapter.

REFERENCES

1. Estes, H. H., and A. W. Fowle. *The ABC of Traffic Control.* Apparatus Department, General Electric, Schnectady, New York.
2. *The PR System of Traffic Control,* Bulletin E-226. Automatic Signal Division, Eastern Industries, Inc., Norwalk, Connecticut, 1957.
3. PRC Voorhees. "Computerized Signal Systems: Overview and Product Summaries." U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1982.
4. PRC Voorhees. "Computer Controlled Traffic Signal Systems." Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1982.
5. Haenel, Herman E. "Texas Stand-Alone Arterial Systems." Presentation Paper, Texas Department of Highways and Public Transportation, 1981.
6. "Type 170 Coordination Program, Basic Arterial System (BASYS)." California Department of Transportation (Caltrans), 1982.
7. "The 3800 Closed Loop System." Transyt Corporation, Tallahassee, Florida, 1983. (Product Brochure.)
8. "The KMC-10,000 Incremental Master System." Econolite Control Products, Inc., Anaheim, California, 1983. (Product Brochure.)
9. "Distributed Traffic Control and Surveillance System." JHK and Associates, Alexandria, Virginia, 1983. (Product Description Booklet.)
10. "Eureka Interconnected Progression System (EIPS) — Program C-1." California Department of Transportation (Caltrans), District Program Summary, Sacramento, California, 1983.
11. Stockfisch, Charles R. "The UTCS Experience." Paper presented at the Transportation Research Board Meeting, Washington, D.C., 1984.

12. Kobetsky, Ken F. "A Proposed Alternative: The Basic Computerized Signal System." Discussion Paper, Transportation Research Board, Traffic Control Devices Committee, 1980.

13. "Micro Control System." PRC Voorhees, McLean, Virginia, 1983. (Product Description Brochure.)

14. "1.5 Generation System Functional Description." Prepared for FHWA by Kessman and Associates, Contract DTFH61-82-C-00091, November 1983. (Draft Copy.)

15. Haenel, Herman E; Alfred H. Kosik; and Blair G. Marsden. "Innovative Uses of Traffic Responsive Control in Texas." Prepared for Engineering Foundation Conference in Henniker, New Hampshire, July 1983.

8. COMMUNICATIONS

CONTENTS

Section *Page*

8.1 INTRODUCTION 8.3
  Purpose 8.3
  Communications and Electronics Evolution 8.3

8.2 BASIC CONCEPTS 8.4
  Communication Link and Signaling Techniques 8.4
  Interconnection 8.5
  Modulation and Demodulation 8.6
  Multiplexing 8.10
    Frequency Division Multiplexing 8.10
    Time Division Multiplexing 8.10
  One-Way vs. Two-Way Communication Links 8.13
  Interface Equipment 8.14
    Communication Interface Unit 8.14
    Modems 8.14

8.3 ALTERNATIVE COMMUNICATION LINKS 8.15
  Wire Pairs 8.15
    Owned vs. Leased 8.16
    Experiences 8.16
  Coaxial Cable 8.17
    Owned vs. Shared Use 8.18
    Cable TV Systems (CATV) 8.18
    Experiences 8.21
  Fiber-Optic Communication 8.22
    Experiences 8.23
  Air-Path Communication 8.24
    Laser 8.24
    Microwave 8.24

8.4 COMMUNICATION SYSTEM PLANNING AND EVALUATION 8.25
  Selecting Transmission Rates 8.25
  Requirements for Communication Link Quality 8.26
  Requirements for Communication Link Reliability 8.26
  Trade-Off among Communication Alternatives 8.26
  Utility/Cost Analysis 8.31

Section *Page*

8.5 ADDITIONAL INFORMATION SOURCES 8.31
  Data Communication 8.32
  Coaxial Cable Communication (CATV) 8.32
  Air-Path Communication 8.33
  Fiber-Optic Communication 8.33

REFERENCES 8.33

271

8. COMMUNICATIONS

8.1 INTRODUCTION

This chapter presents an overview of communications technology, with emphasis placed on its impact upon traffic control systems. Basic communication concepts for systems are first described, followed by alternative communication media. Following a consideration of the operational constraints imposed on the communication system, the chapter concludes with a discussion of guidelines for system planning and evaluation.

Purpose

The purpose of this chapter is to provide the reader with sufficient knowledge to fulfill the following functions:

- Develop a basic understanding of the terminology of the communications field, especially as it applies to traffic control systems
- Understand broad concepts of the communication system operation
- Compare the ever-increasing number of different types of communication media and their associated operating characteristics
- Compare and evaluate communication systems specifications and proposals
- Understand advice or suggestions given by systems advisors, consultants, or salesmen
- Make sound decisions in the selection of communication components from the control system planning and evaluation process

Communications and Electronics Evolution

Traffic control systems and connecting communication links began when it became desirable to physically connect one or more local signal controllers so that a reliable timing relationship between intersections could be established and maintained. In these original small-scale systems, a simple 2-conductor interconnect line was used, with one of the controllers utilized as a master control unit to assure synchronized operation of the local units.

As traffic control systems grew in size, more and more local controllers were interconnected to a master control unit. The multidial operation of systems required the addition of conductors to the interconnection (communication) links; and, because the intersections were no longer all in the immediate vicinity of the master control unit, longer and more costly communication paths were required. The electromechanical traffic control systems, many of which are still in use, are examples of the use of an early version of the communication link with two or more conductors each providing some on/off control or sync pulse function.

In such systems, the interconnect circuit, using the multiconductor cable, operates by ON/OFF switching of 110-v AC to provide sync pulses, dial, or offset selection. The switching originates at the master control unit via a contact opening or closure. Typically, the contacts are operated at the master unit by a time clock, coil-type relay, and by dial keys.

Direct-wire communication has been utilized in a different manner in the PR-type systems (*1*). These control systems used a 3-phase electrical interconnect, in which the AC cycle rate was varied to produce different system cycle lengths by controlling the speed of the local synchronous motors driving the respective dials. Offset reference points for the system were produced by a separate set of conductors.

The direct-wire communication concept is presently in use in systems of various types including electromechanical and solid-state pretimed, PR-type, solid-state full-actuated, and computer-controlled systems, both small and large. Although the electronics hardware employed has changed, the basic control concepts described above remain.

The development of solid-state switching devices, such as the transistor, has significantly impacted the physical nature, as well as the functional concept, of communication systems used in traffic control. The integration of solid-state circuitry has progressed rapidly. Early small-scale integrated (SSI) circuitry performed only very basic tasks, such as making simple ON/OFF control decisions. Medium-scale integrated (MSI) circuits allowed counting, sequencing, or simple arithmetic operations to be performed within a single circuit element no larger than a sugar cube. Large-scale integrated (LSI) circuits containing 100 or more transistors and other circuit elements in a miniature envelope allowed complete computing and calculating capability within a single package. With the cost/capability/size relationship offered by these devices, all traffic control hardware has changed dramatically. Not only has the computer become a rather commonplace device for central control of both large- and small-scale signal systems, but the microprocessor has become the basic electronic unit utilized in nearly all master and local signal controllers presently manufactured.

The use of computers and microprocessors in traffic control systems allows communication links capable of high-speed data transmission, especially when 2-way data exchange is employed for system surveillance and the real-time display of functions. Because of the demands placed upon the modern communications system, more involved concepts (multiplexing, multidrop connections, etc.) have become necessary. These sophisticated methods are costly, but they do offer the ability to transfer large amounts of data over fewer conductor/cable miles. Communication costs have thus become a major factor in traffic control system planning.

8.2 BASIC CONCEPTS

Communication is defined as the transfer of information from one location to another. The form of the transfer of information can range from voice or hand signals between individuals to complicated coded signal data sent and received between ground station and satellite (air-path medium), or between points via cable wire pairs (physical medium). Some examples of communications in the traffic control field include the following:

- Electrical links between local traffic signal controller units and hardware components, such as the use of switching conductors from a pedestrian-operated pushbutton to the controller assembly — (This type of communication link will not be included in discussions in this chapter of the Handbook.)
- Communication link from a traffic detector station to a data-collection location, perhaps several miles away, used for the transfer of traffic flow or vehicle count data
- Communication links between a local signal controller and a master controller, subsystem master unit or central computer, used for the 2-way flow of data: control commands to the local; status or other data from the local to the respective supervising control unit

Communication Link and Signaling Techniques

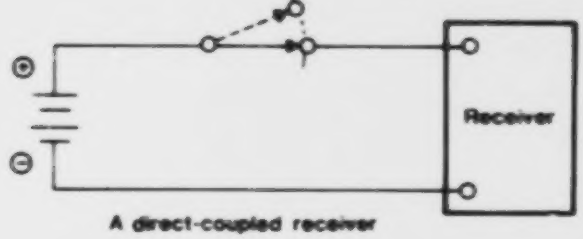
The path over which information is sent is commonly referred to as a link or a channel. A link is described not only in terms of the point-to-point path that it interconnects, but also on the information capacity that it possesses. The makeup of the link (air-path or physical) affects certain characteristics of the link, including distance capabilities and capacity for carrying information.

The information-carrying capacity of a link is generally described in two ways. One is the time during which the link (channel) is available. Thus, if a link is of the shared-use type, as in a telephone party line, the capacity available to each user is reduced. A second parameter is the bandwidth of the link (channel), which is a technical term describing the range in sinusoidal frequencies (referred to in Hertz or Hz, where 1 Hz is 1 cps) that can be transmitted through the link (channel) without significant attenuation (weakening) or distortion. Generally, the wider the channel's bandwidth, the greater the amount of information that can be passed along the link in a given period of time.

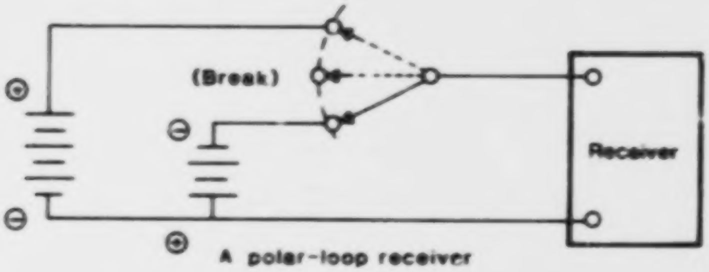
Direct-wire links between two points in a traffic control system are driven by a contact closure or by an electronic switch carrying the signaling voltage from the source to the receiving element. Examples of two direct-wire switching techniques used are shown in Figure 8.1:

- The simple direct-coupled link — A link in which electrical power is either present or absent, depending respectively upon contact closure or opening.
- The polar-loop technique — A technique in which a positive voltage is sent when the signal source is active, and a negative (reversed) voltage is sent when the signal source is inactive. This technique increases the ability of the receiver to distinguish between the ON (positive voltage) and OFF (negative, reversed voltage) of the transmitter. It also allows the receiver to identify a third state, a break in the link, when neither a negative nor positive voltage is received.

For longer links, the simple direct-coupled or polar-transmission methods are not generally used. As the conductor length increases, the voltage signal produced by the transmitter is reduced in strength by wire resistance. Also, unwanted signals are introduced into the link, since the longer conductors act much like a radio or TV antenna, picking up the electromagnetic signals produced by atmospheric conditions, electrical machinery, passing vehicles, and many other sources. Such signals are commonly called line noise, and, just as the static on a radio can obscure a weak station, the noise picked up over a long direct-wire link can override the weakened signal making it impossible for the receiver to determine the value of the signal. As a result, for distances in excess of one mile, more complex signal techniques are generally employed.



A direct-coupled receiver



A polar-loop receiver

Figure 8.1. Examples of direct-wire switching techniques

A variety of sophisticated transmission techniques is available to the communication system designer faced with the linking of widely separated components. In most traffic control applications, the information to be transmitted is 2-valued:

- A signal lamp is ON or OFF
- A traffic sensor indicates VEHICLE or NO VEHICLE
- A contact closure is OPEN or CLOSED

As a result, the data transmission techniques used are intended for only 1 of 2 possible values at any given time. In such systems, which are commonly referred to as binary transmission systems, binary indicates the 2-valued nature of the communication data. Each 2-valued item of information tells the receiver about the state of a single YES or NO value, and groups of these items may be used to represent more complex items of information that can take on more than the two values, yes *or* no. A single 2-valued unit of information is known as a bit (a contraction of binary digit), and values which a given bit takes on may also be called TRUE/FALSE, ONE/ZERO, or MARK/SPACE. Groups of bits can be used to represent numerical data by using the binary numbering system.

For further information on the binary numbering system and digital logic, the reader is referred to Chapter 3 of *Computer Controlled Traffic Signal Systems* (*2*).

Interconnection

In organizing a communications network, one factor is the way various data receivers and the data source, or sources, are to be interconnected. The most direct method is point-to-point, as shown in the example of the simple traffic control system in Figure 8.2. In this method, separate links are provided between each receiver and the data source, with the receivers assumed to be at geographically separate locations. Point-to-point interconnection is a common technique, since having only one receiver on each line simplifies the sequence of control characters and data exchanges between the data source and the receiver. The disadvantages in the point-to-point method include the following:

- Failure of a link totally isolates that receiver from the central facility
- Increased communication costs, especially in larger systems
- Untenable number of cables returned to central facility in a very large network
- Sophisticated communication signal methods cannot

274

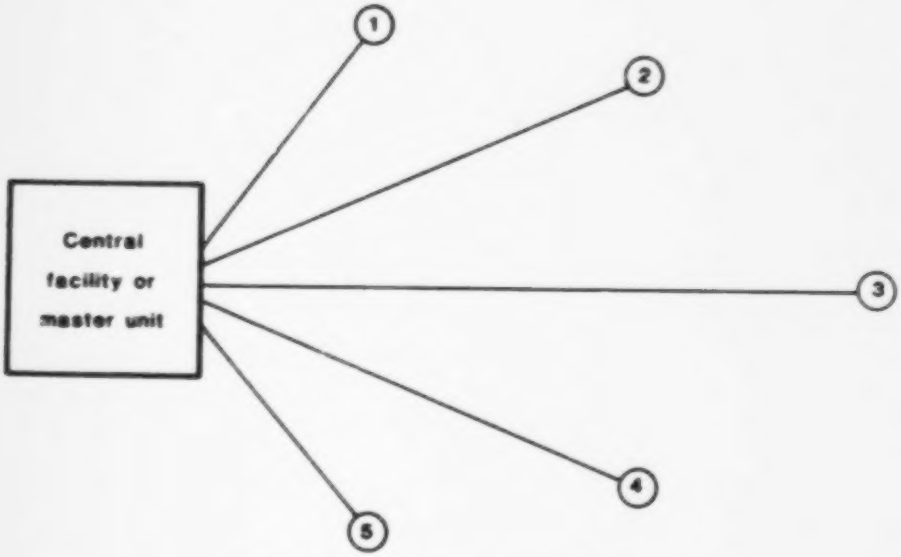


Figure 8.2. Point-to-point interconnection

be used to share channel capacity between receiver points

An alternative arrangement used in many systems, especially when the cost of point-to-point connection becomes prohibitive, is the multidrop scheme shown in Figure 8.3. If the loop is closed back to the central facility, then the arrangement is also referred to as a closed-loop linkage. Multidrop interconnection unites two or more receivers on the same link (channel), thus reducing channel costs. Because of the presence of multiple receivers on the same line, the scheme used for sequence of control characters and data exchange.1 must be expanded to include special control sequences for establishing communication between the data source and the proper receiver. This is accomplished through use of a unique address identifier. Upon seeing its own address, the selected receiver will then copy only the transmitted data intended for its reception. When a particular receiving station in a multidrop system is selected prior to sending it some data, it is said to be addressed.

Figure 8.4 illustrates the multidrop communications link scheme as applied to a large signal system network in which trunkline and branch drops are utilized.

Modulation and Demodulation

Binary transmission systems have two basic signal values at any given time. Thus, a single bit value is either ONE or ZERO. In order to transmit a binary signal over a transmission path that is not directly coupled, some type of modulation/demodulation system must be used. Modulation is the process by which the differing values of an item of information (for example ONE or ZERO; ON or OFF for a given bit) are converted into certain signals. Transmission of binary data elements requires a digital or discrete modulation system. Such a system usually employs two different signals (e.g. MARK/SPACE) which represent ON/OFF and ONE/ZERO, respectively. The process of receiving the modulated signals and reconstructing the original data values from them is called demodulation. The necessity for devices to perform both of these tasks is a requirement for 2-way operation on the same channel. A device possessing both of these qualities is called a modem.

The modulated signals need to propagate well over the selected communication medium. Thus, most modulation systems begin with a sinusoidal tone that is well within the preferred bandwidth of the channel to be used. This signal is called the carrier signal. During the modulation process, the characteristics of the carrier are changed in some manner to represent the differing bit values that are transmitted. For example, a typical telephone (voice-grade) line has a bandwidth of 2,700 (H) or cps. The range is 300 Hz to 3,000 Hz, the range in which the human voice is readily intelligible. Thus, a typical carrier signal for use with a voice-grade channel would

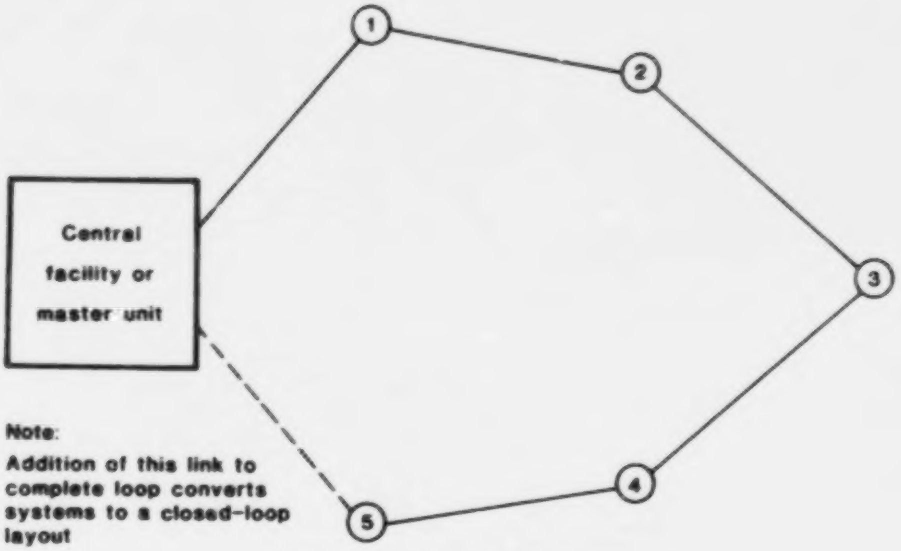

1
2
3
4
5
Central facility or master unit
Note:
Addition of this link to complete loop converts systems to a closed-loop layout

Figure 8.3. Multidrop interconnection

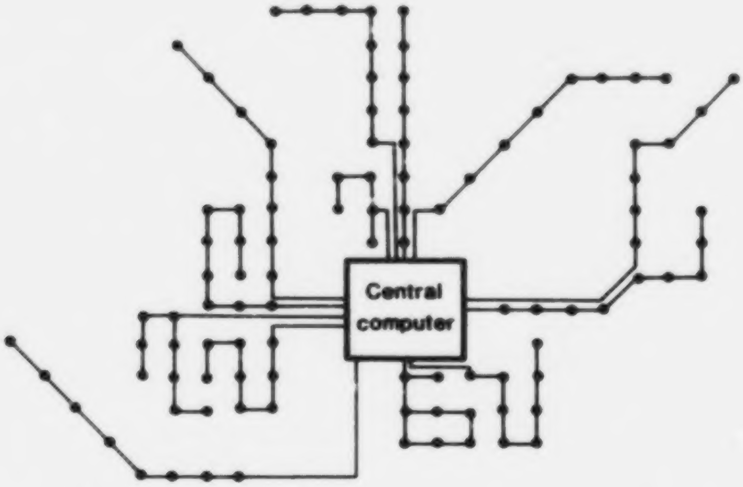

Central computer

Figure 8.4. Application of multidrop scheme in a large signal network

be a sinusoidal signal operating at 1,650 Hz. This signal is centered in the usable bandwidth of the channel.

The modulation process changes the characteristics of the carrier signal so that it reflects the different values of the information being transmitted. The three modulation processes are described as follows:

- Amplitude modulation (AM) changes the strength of the carrier, using a signal of large amplitude to represent the ON or MARK condition, and a signal of

276

lesser amplitude to represent the OFF or SPACE condition. The AM demodulation function involves the measurement of the received signal strength of the carrier frequency. If the received strength exceeds some threshold value, the demodulator indicates a MARK or ON output. Because the valid reception of an AM signal depends upon the measurement of the received signal strength, it is possible for line noise to severely degrade AM reception. For that reason AM is not often used in traffic control communication systems. The relationship between the signal strength and the strength of the noise signals is commonly called the signal-to-noise ratio. The higher the ratio at the receiver, the better will be the quality (i.e., the more noise-free) of the channel. Figure 8.5 is a simplified graphic of amplitude modulation.

- Frequency modulation — In order to improve transmission performance in the face of extraneous noise on the communication channel, one of two frequency modulation (FM) systems is commonly employed. Both of these schemes vary the frequency of the transmitted carrier signal in order to represent differing signal values. In a binary transmission system, FM takes the form of frequency-shift-keying (FSK) transmission. The technique can use either two or three discrete signaling frequencies. If two frequencies are used (called 2FS or 2-FSK transmission), one frequency represents the MARK or ONE condition and the other represents the SPACE or OFF condition as in Figure 8.6. When 2FS transmission is used the IDLE condition (the absence of any signal) can only be handled by turning the modulator off (no signal). Since this condition is the same as that present with channel breakdown, channel interruption is quite difficult to detect with 2FS. As a result, three frequencies are often employed (called 3FS or 3-FSK transmission) in traffic control communications. Here, a third carrier frequency is used to represent the IDLE condition. This third frequency is generally centered between the MARK and SPACE frequencies, to make it easier for the demodulator to separate the different frequencies. Because the received signal strength is measured only after passing through a relatively narrow band filter in the demodulator, FSK offers an improvement over AM transmission techniques. The noisy signal received at the output of the channel is applied to filters that are narrowly tuned to MARK, SPACE, and IDLE frequencies. Since the selective filters only respond to the respective signal frequencies, only noise in those signal frequencies are passed on, thus improving the signal-to-noise ratio. FSK, or some closely related technique, is the most commonly used method for transmitting digital information in traffic control systems.

- Phase modulation — Closely related to FSK is phase-shift keying (or PSK). In this technique, the phase of the carrier signal (relative to a constant-phase reference signal) is varied to represent differing signal values. In a binary system, the phase is usually shifted 180° to represent a MARK, but left unchanged to represent a SPACE. Thus, the MARK/SPACE value is represented by a change in signal, rather than by a given signal condition (as in AM or FSK). A typical PSK signal is shown in Figure 8.7. By using smaller changes in phase to represent more than two signal values, more information can be sent through a channel in a given period. Because a reference phase must be generated at the receiver, PSK is somewhat more difficult to demodulate than FSK. The reference phase must be present to measure signal phase changes. PSK offers some improvement in signal recovery if the signal-to-noise ratio is low.

Both the FSK and PSK techniques are quite common in traffic control communication applications.

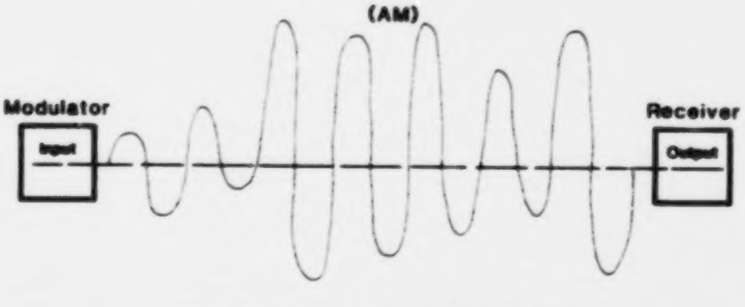


Figure 8.5. An amplitude-modulated signal

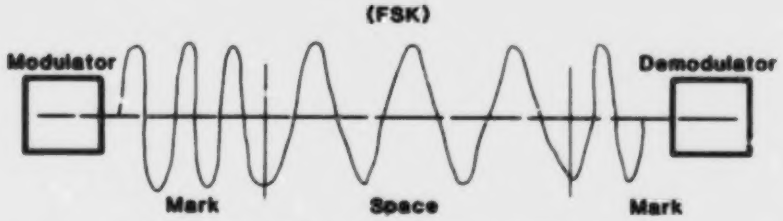

(FSK)
Modulator
Demodulator
Mark
Space
Mark

Figure 8.6. A 2-frequency, frequency-shift-keyed signal

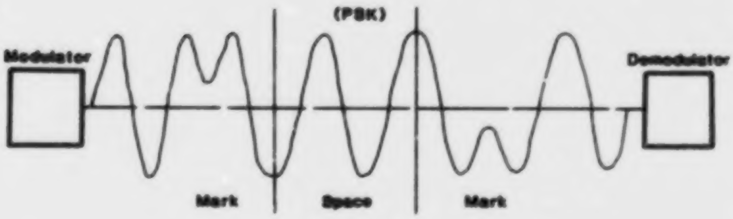

(PSK)
Modulator
Demodulator
Mark
Space
Mark

Figure 8.7. A phase-shift-keyed signal

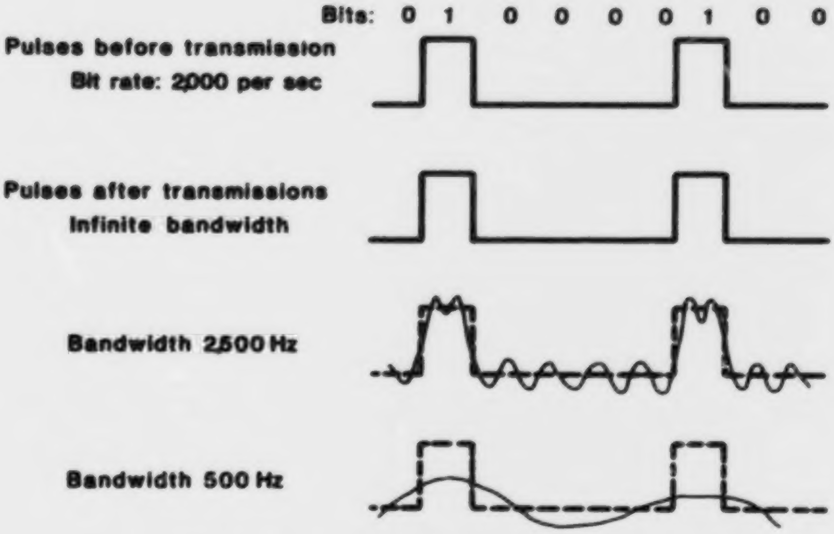

Bits: 0 1 0 0 0 0 1 0 0
Pulses before transmission
Bit rate: 2,000 per sec
Pulses after transmissions
Infinite bandwidth
Bandwidth 2,500 Hz
Bandwidth 500 Hz

Figure 8.8. The communications channel and its capacity

Source: Reference (*2*)

Multiplexing

Multiplexing can be defined as a technique which combines several communications channels into one facility or transmission path.

Before discussing the specific multiplexing techniques, the following information regarding some other communication characteristics is appropriate:

- Bit rate — The measure in bits per second (bps) of the digital information being transmitted (and received). For example, if the duration of a bit in a multiplexing technique is 0.001 sec, the equivalent bit rate is 1,000 bps. In communications, bit rate and bandwidth do not appear to be related, but there is, in fact a direct relationship. If an attempt is made to send bits over a given bandwidth at too high a rate, they become blurred and uninterpretable. To transmit a bit stream at a rate of 1,000 bps exactly, with no distortion at all, would require an infinite bandwidth. Even at 25,000 Hz (25 kilohertz, 25 KHz), the pulses suffer some distortion, and as the bandwidth decreases, the distortion becomes worse until at 500 Hz, the signal can barely be discerned. Both effects are shown in Figure 8.8.

  To achieve rates above 1,200 bps, complex modulation, demodulation, and error correction techniques are necessary. Because of cost, reliability, and maintainability factors of sophisticated electronics required, these techniques are not normally employed in traffic control systems. A practical guideline to follow is a bit rate which does not exceed one-half of the available bandwidth, in Hz. As an example, on a voice-grade telephone line, a bit rate of 1,200 bps should not be exceeded (*2*).

- Baud rate — The communications system cannot be used to its fullest bit-rate capacity because of the need to transmit extra bits related to the operation of the communications system and to eliminate interference from adjacent channels. In other words, the number of bits of traffic control data being transmitted is less than the total number of bits being transmitted. The rate at which the actual traffic control data bits are transmitted is known as the baud rate. The baud rate, thus, is usually considerably less than the actual bit rate (*2*).

Frequency Division Multiplexing. Frequency division multiplexing (FDM) may be thought of as a parallel transmission system with data being transmitted simultaneously from several sources over the same medium. This process, in effect, breaks the total available bandwidth into a set of channels, each of which occupies a portion of the band. The frequencies assigned to these channels within the bandwidth, must not overlap. In fact, in order to assure separability at the receiver, guard bands of unused frequencies must be provided between channels.

For wire transmission, a commonly used group of standard channel frequencies spaces each channel 120 Hz from the adjacent one (center frequency to center frequency). The lowest (center) channel frequency is 420 Hz and the highest (Channel 23) is 3,060 Hz. A ±30 Hz tone shift, i.e., 60 Hz is used between the MARK and SPACE state of each channel. This mark-to-space frequency range allows for guard bands 60 Hz wide. Figure 8.9 illustrates the channel and guard band configuration for Channels 1, 2, and 3. Frequency shift keying (FSK) is commonly used in FDM, and its use is assumed in this discussion.

FSK can utilize either 2-frequency state (2FS) or 3-frequency state (3FS) schemes when used in FDM. These schemes were previously discussed in the modulation and demodulation section of this chapter.

In FDM, different channel frequencies are transmitted on the same line simultaneously. Specific channel frequencies are sorted out electronically at the receiving end, with separate modulation required for each channel. The modulated signals are combined, or mixed, and then sent through the channel. At the receiver, frequency-sensitive filters separate the channels, and each signal is then demodulated. The filters at the receiver must be designed to separate the channels properly. Generous guard bandwidths reduce the electronic sophistication required for filtering, and thus decrease the cost of receiving equipment.

FDM allows a single channel to act as if it were a group of independent signal paths, each of which could then be used to carry a single bit of information. Higher quality FDM systems can separate a single voice-grade line into 20 or more channels. FDM at the radio-frequency level is also used in communication systems employing a coaxial cable. The cable's broadband characteristics permit two-way communications over a much greater number of channels than can be attained with a voice-grade line. This technique can also allow space for multiple TV channels and camera control channels on the same single cable.

Time Division Multiplexing. The previous discussion of FDM indicated that all of the transmitting devices are connected through modulators to the communications line. Each modulator transmits information at a different pair (MARK/SPACE) of frequencies. One frequency of the pair is always being transmitted from each device.

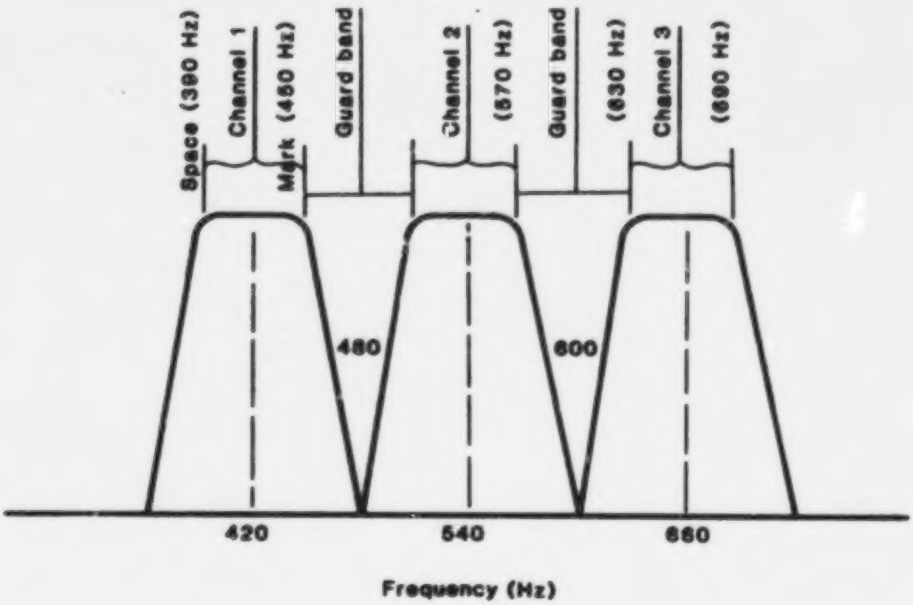


Figure 8.9. Channels and guardbands utilized in frequency division multiplexing (FDM) with frequency-shift keying

Therefore, all of the 2-frequency modulators are continuously transmitting information that is being received and selected by demodulators at the receiving end (*2*).

An alternative to frequency-division multiplexing (FDM), in order to send digital data from one point to another, is the use of time-division multiplexing, or TDM. This technique operates by time-sharing the communication lines, capacity rather than by parallel full-time, frequency-based sharing. Thus, the channel is used to carry one bit of data at a given time. As time passes, successive bits are sent through the channel, one after the other. TDM is also referred to as a polled or supervisory-type system. When digital data are transmitted serially, the data source must assemble the data into strings of ON/OFF or MARK/SPACE binary values. These strings, often characterized as a sequence of ones and zeros, such as 101101, must be sent through the channel, received, and properly interpreted at the other end of the channel.

The use of TDM complicates the operation of a communications system. The channel then no longer serves as a point-to-point data path, but carries one item of information at one time, another at a later time, and so on. In order for the receiver to properly interpret and act upon the data that it receives, it must be able to identify two types of timing information:

- Bit synchronization enables the receiver to distinguish between successive bits within a string of data. To accomplish this, the received signal must be measured, and based on the measurement, the value (MARK or SPACE) estimated. The value changes as new bits are received. The receiver must know the rate at which the data are transmitted so that it can predict when a new value will arrive. Bit synchronization also involves the avoidance by the receiver of periods of changing value that occur between bits in the data string.

- Word synchronization involves the valid separation of a string of received bits into the groups (characters, words, or bytes) that legitimately go together to create the string. The two approaches to word synchronization are:

    - Asynchronous transmission, in which a prefix and suffix are attached to each transmitted word. Commonly, the line is kept in the MARK condition between words. Then a SPACE bit is used as a prefix or START bit, and a MARKING time period equal to more than one bit is always allowed between the end of one word and the start of the next. This period allows for interword separation, and is referred to as the STOP bit time. Since each word is preceded by a SPACE value, the receiving equipment can monitor the output signal from the line waiting for a MARK to SPACE change. This change provides both bit and word synchronization.

The receiver delays for one-half the bit time, which is the period for which each bit is transmitted. It then samples the received value at successive bit times in order to determine values of the bits which make up a word. The START bit serves no other purpose than providing a means of synchronizing the receiver to the transmitted data string. The STOP bits allow the receiver some time during which it can store or otherwise operate on data previously received. This delay also assures that at least one MARK bit separates the last data bit of one word and the START bit of the next that might follow it. Asynchronous transmission is portrayed in Figure 8.10.

○ Synchronous transmission — For most traffic control applications, the simplicity and low cost associated with asynchronous transmission make its usage quite desirable. When data must be transmitted at higher rates, as between two separate control computers, synchronous transmission is utilized. In this scheme, synchronizing information, usually in the form of several repetitions of specially designated group of bits (sync word), is sent only occasionally. Thus, data are sent for longer periods without interruption, thereby improving the baud rate. The use of synchronous transmission increases the cost of the transmitting and receiving equipment. The oscillators on each line end must maintain sufficiently close tracking over a much longer time period, and control logic for recognizing the special sync word must be provided.

In TDM, the message transmitted by the master unit at central, besides carrying the address, typically contains command and control data and check bits utilized for error-detection. The return message from the remote site contains controller and detector status as well as error detection bits. Each remote set is polled (interrogated) in sequence, and the duration of the polling cycle, is the time required to poll all of the remote units on the line. This cycle is a function of the hardware and number of drops on the line, with the maximum permissible duration being a function of the processing algorithm and data encoding technique utilized. Since, in TDM, events are not transmitted in real time, as in FDM, it is necessary to encode the occurrence of events, such as the passage of a vehicle over two detectors. One method is by providing accumulators to record the numbers of vehicles which have passed since the last interrogation and the duration of the period that vehicles were over the loop (presence period). In distributed processing systems, the parameters necessary to control traffic are calculated at the remote site and then transmitted to central, thus reducing the required interrogation rate. These parameters may include volume, occupancy, and speed averages for several minutes (*3*).

Various manufacturers utilize different synchronizing techniques, data formats, and error-detection schemes. Some utilize one single word containing all the data while others transmit a message containing several short words. Examples of short and long word schemes are shown in Figure 8.11. In each of the cases, the message is prefixed by a synchronizing bit (or bits) to allow the receiving equipment to synchronize with the transmitting site. The single long word format has the advantage of more efficient utilization of the channel, thus not requiring the additional start, stop, and space bits of the multiple-word message. The latter technique does, however, have greater flexibility, with the number of words in the message being tailored to the data requirements. Thus, if an intersection contains only one detector, generating 8 bits of data, a message format utilizing 8-bit words is more suitable than one using 32-bit words. In the example shown, the message returned from the remote site is prefixed with its address so that the master knows that the proper site has received and understood the message. Such address acknowledgment is a form of error detection used in some, but not all, TDM communication methods (*3*).

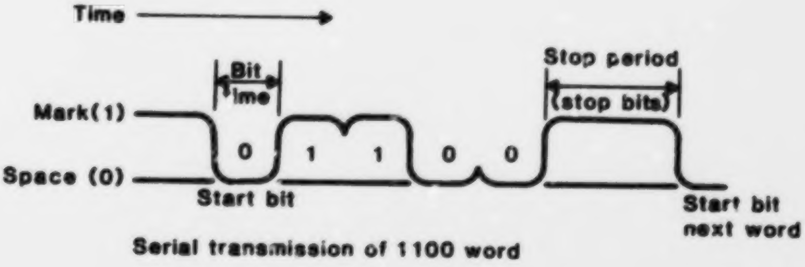


Figure 8.10. Asynchronous transmission

For those TDM systems utilizing FSK, the frequency shift in Hz is from one-half to three-quarters of the maximum bit rate, and the bandwidth required is equal to about twice the maximum bit rate. The relationship between maximum allowable bit rate and the frequency shift for a practical system is complex, and it depends upon the signal-to-noise ratio and the filter characteristics of the receiver and transmitter (*3*).

Higher rates and more efficient utilization of the bandwidth in wire-pair systems can be obtained by utilizing phase-shift keying (PSK) or differential phase-shift keying (DPSK). With this technique, the change in phase conveys the information (*4*), and methods have greater noise immunity than FSK. Data rates up to 9,600 bps can be attained by amplitude modulating each phase change of an 8-phase DPSK system, with each symbol thus representing four data bits. The modems utilized in both PSK methods are more costly than FSK modems, and are also more sensitive to the phase bits (sudden changes in phase) which sometimes occur in the leased private-line service (*3*).

The TDM data formatting and decoding can be implemented in either hardware or software. The software approach can result in a cost saving if microprocessor-type controllers are utilized at intersections. In this scheme, a modem is provided to transmit and receive the data while a universal asynchronous receiver transmitter (UART) or similar type device is used to convert the serial data transmitted over the medium to a parallel form suitable for use by the processor.

One-Way vs. Two-Way Communication Links

The three classes of communications links include the following:

- The simplex link, which allows flow data in only one direction
- The half-duplex link, which allows data flow in either direction, but operates in only one direction and, in a given time frame
- The full-duplex link, which allows data flow in both directions simultaneously

A simplex line, the least expensive way of connecting two points, requires only one modulator and one demodulator since the data flow is unidirectional. Because the use of a simplex link does not provide for any form of answer-back, status reporting, or validity checking, the data source can only assume valid operation and

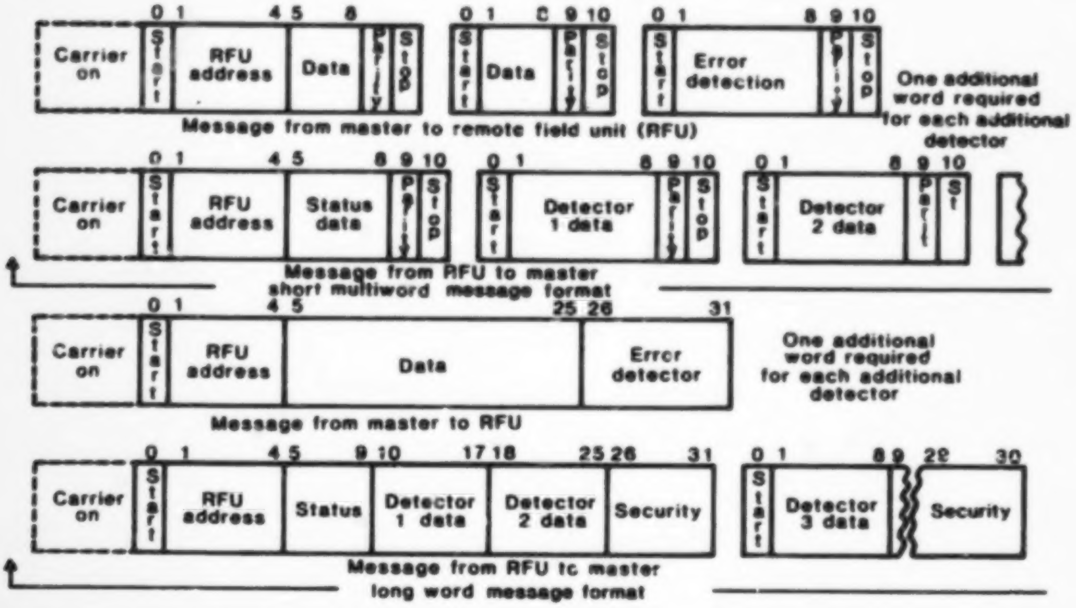

Carrier on
Start
RFU address
Data
Parity
Stop
Error detection
One additional word required for each additional detector
Message from master to remote field unit (RFU)
Status data
Detector 1 data
Detector 2 data
Message from RFU to master short multiword message format
Error detector
Message from master to RFU
Status
Security
Detector 3 data
Message from RFU to master long word message format
0 1 4 5 8 9 10 17 18 25 26 29 30 31

Figure 8.11. Typical time division multiplexing (TDM) message formats

Source: Reference (*3*)

continue sending data, while possible transmission errors or failures go undetected.

The use of the half-duplex communication necessitates some control capability at each end of the link. At a given moment, the modem at one end of the line must be acting as a modulator, while the modem at the other end demodulates the received signal. If both are ever allowed to assume the same mode, the link becomes inoperable. The control units at each link end must each assume that the modem at its respective end of the link is in the proper mode. When transmitting in either direction, however, the full capacity of the channel is available. A typical operational sequence begins when the communications interface unit (CIU) at the central unit selects a given link connection and switches the modem at that end of the link to the transmit mode. An initialization process, or a time-out sequence, selects the receive mode for the modem(s) at the opposite link end. The CIU then sends a block of data, via the central modem, to the receiving unit and, in order to verify valid reception of this block, switches the central modem to the receive status.

Upon reception of an end-of-block code following the data bits, the receiving (at controller end of link) unit switches its modem to the transmit mode and sends a response (OK, or not OK) back to the CIU via the central modem.

The process described above, which is known as turning the line around, may be somewhat time consuming. For example, the modems may require a specific delay period for reversing their function, and the channel (link) itself may introduce delays before it settles to the new conditions. If the operation requires frequent line reversals, the baud rate (the effective data rate) may be seriously degraded. Also, the exchange of control characters to mark the beginning and ending of data blocks or to signal the validity of data reception will reduce the baud rate.

Operationally, a full-duplex link can be considered as being 2 parallel simplex links operating in opposite directions. Full-duplex capability can be achieved by using 2 separate channels (hence, the term "4-wire connection") or by frequency multiplexing the two directionally opposed signals within the same channel. Thus, the provision for a full-duplex link either raises the cost of the channel(s) or, if frequency multiplexing is used on a single channel, reduces the 1-way capacity available for data transmission.

The sequence of control characters and data exchanged between data source and receiving units is commonly called line discipline. The operational sequence may vary from system to system. The handling of line discipline is required of the CIU and of all receiving units. As the complexity of the sequence of control characters grows, so will the cost of equipment that must be utilized to handle it.

Interface Equipment

Although the following is written in the context of computer control of traffic signals, the equipment described is also applicable to master type control systems and subsystems.

Communication Interface Unit. The central system master not only monitors traffic conditions, but also effects the control of traffic signal indications. It is this 2-way path; data input for surveillance, monitoring and status checking, and data output for control and activation, that creates the communications needs for the traffic control system. To alleviate overloading of the central system master unit (computer) with the described communications tasks, a communication interface unit (CIU) is employed. The CIU is a computer-like device that is capable of handling, at the central control location of the system, all or part of the communications interface requirements. CIU tasks include the following:

- Periodic status checking
- Error handling
- Data bit message sequencing
- Synchronization of data bits and word bits
- Modem control
- Other tasks associated with the operation of the communication system

By off-loading these functions from the system master, more of its capability is made available for calculating control algorithms and other functions. In smaller systems, the communication control may be handled entirely by the central processing unit.

Modems. The modem (modulator/demodulator) serves as the interface between the data source and the communications link on one end. It also interfaces the other end of the link with the data receiver. In a sense, the function of the modem is invisible to the system, since the data seen by the receiver are expected to be identical to the original data at its source, and the actual modulation/demodulation technique and channel characteristics are not of concern. These parameters do, however, affect both transmission rate and reliability (the probability that erroneous data are received). But, from a systems overview, these aspects can be lumped as interior to the channel description.

283

For a simplex channel, a true modem is not required, since the source only transmits or modulates, and the receiver only demodulates. However, both half-duplex and full-duplex transmission require true modems, since both modulation and demodulation are employed at each end of the link.

Modems are usually characterized by the transmission rate that they will allow. Low-speed modems handle transmission rates up to approximately 500 bps, with the intermediate type allowing rates to 1,200 bps. Medium-speed modems cover the 1,200 to 2,400 bps range and require conditioned voice-grade lines.

For higher transmission rates, e.g. from 2,400 to 9,600 bps, more expensive modems are required. These modems generally use a synchronous transmission technique and operate only over conditioned voice-grade lines or other media with very wide bandwidth. Since synchronous transmission requires closely controlled modulation and demodulation techniques, the cost of high-speed modems is usually several times that of their medium-speed counterparts. Few traffic control systems have need for data transmission rates in excess of 3,000 bps.

To better understand modems, the terms associated with their operation are defined as follows:

- Request to send (RTS) is an electrical signal applied to the modem by the data source notifying the modem that data is ready to be transmitted.
- Clear to send (CTS) is an indication by the modem to the data source that it (the modem) is prepared to transmit. A clear-to-send delay, the length of which is programmed into the modem, allows the receiving modem time to detect and lock to the transmitting modem's carrier before data transmission commences.
- Carrier detect turn-on time is the time it takes for a receiving modem to turn on its signal detector after it detects a carrier from a transmitting modem.
- Carrier detect turn-off time is the time it takes for the receiving modem to turn off its signal detector after detecting loss of carrier or soft carrier.
- Soft carrier is the transmission of a specific frequency, below the MARK and SPACE frequencies at the end of a transmission, to avoid spurious signals caused by the sharp transition that would otherwise occur if the carrier were turned off. The receiving modem turns off its signal detector upon detecting this signal.
- Turnaround time is the time required to reverse the direction on a half-duplex line.

8.3 ALTERNATIVE COMMUNICATIONS LINKS

In order to accommodate the increased amount of information transmitted and received in a modern traffic control system, the performance requirements of the communication media are much above those found in a parallel hard-wire interconnected system. The medium must be capable of carrying signals with a minimum of interference from adjacent conductors or from external sources. Several types of communication links are discussed in this section. Some have proved successful, while others have had very limited use in traffic control systems.

Wire Pairs

The communication medium most widely used in traffic signal control systems is the twisted-wire-pair cable. A twisted-pair cable consists of sets of two wires that are wrapped around each other. The twisting of each pair minimizes interference from external sources because the pair of conductors carrying the signal are always immediately adjacent to each other in the cable. Therefore, the induced signal from the interfering source will have the same noise effect on each conductor of the pair. Since the receiver is only measuring the difference in voltage between the conductors, the fact that both conductors have the same induced voltage will not be noticed. As is indicated in Figure 8.12, a twisted-pair cable also reduces interference known as cross-talk between adjacent pairs (or lines) because the same current is flowing in opposite directions in each conductor. Therefore, the electric field radiated from the two conductors is in opposite directions (radially around each wire), which results in the two fields canceling each other out (*2*).

When twisted-pair cable is used as the communication medium in a traffic signal system, it is usually of the voice-grade type. This term (voice grade) is derived from the voice telephone usage of the twisted-pair cable, and, as mentioned in a previous section, the usable bandwidth ranges from 300 Hz to 3,000 Hz, the audible frequency range of the human voice. A voice-grade cable will accommodate a rate of 1,200 bps. If a higher data transmission rate is required, the twisted-pair cable must be conditioned by the addition of electronic equipment, such as loading coils in order to improve Hz transmission characteristics. Standard twisted-pair cable is manufactured in numbers of pairs: 6, 12, 18, 25, 50, 75, 100, 150, 200, 300, 400, 600, and 1,200; in wire gauges 19, 22, 24, and 26 AWG; and it is furnished in reel lengths from 1,000 to 10,000 ft.

Twisted-pair cable for communications may take the form of the private-line voiceband media leased from the local telephone company. Single point or multipoint

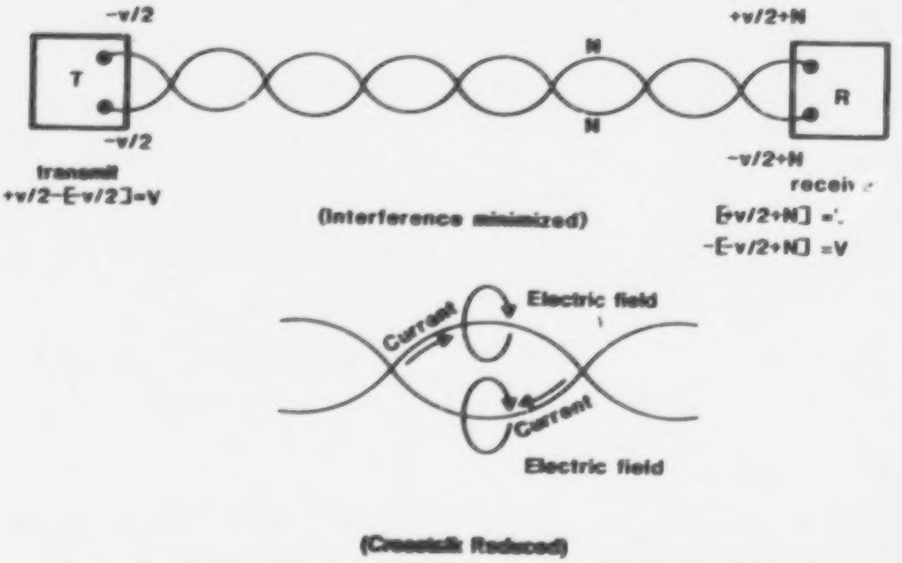


Figure 8.12. Properties of twisted wire pairs and their effects on interference and crosstalk

Source: Reference (2)

drops may be utilized. Most local channel specifications conform to the characteristics of the Bell Telephone System Interstate Tariff FCC No. 260, which defines the voiceband private line as a Type 3002 channel. Significant features of this channel important to communications system design are as follows:

- Maximum allowable transmitter power level
- Signal level expected at the receiver
- Limitations on number of drops on a multipoint line

Voice grade service comes in various standards of quality. As line quality (conditioning) increases, usable bandwidth and data transmission rates increase. Better line-noise ratios and distortion characteristics are also attained over conditioned lines. As might be expected, the quality of line conditioning is cost related; better conditioning does cost more.

The installation of twisted-pair cable is done by one of three methods:

- Underground, in conduit or multiduct
- Underground, by the direct burial method
- Aerial, utilizing existing pole system, if available

These methods for twisted-pair cable installation are also employed in the placement of other types of cable. Discussion of the advantages and disadvantages of cable installation methods is contained in a subsequent section of this chapter.

Owned vs. Leased. When twisted-wire-pair cable is selected as the communication medium for a traffic signal system, the designer and/or owner have the option of utilizing a leased cable or a user-owned cable system, or a combination of both.

The majority of traffic signal systems presently in service, utilize user-owned twisted pair cable for network communication. The capital costs for this medium represent a substantial part of the overall system cost, especially when the cable is installed underground in new conduit. Table 8.1 draws a comparison, from various aspects, between user-owned and leased wire-pair cable.

Experiences. Probably the single factor which most influences the decision of a system designer or owner concerning the use of leased or user-owned communication cable is the ever-spiraling high rates for telephone service. In almost all cases, the higher service rates awarded to telephone companies throughout the country affect the monthly lease rates for leased voice-band channels used for communications in traffic signal systems.

285

Table 8.1. User-owned versus leased wire-pair cable

Feature	User-Owned	Leased
Capital cost	High — especially when installed underground in new conduit	Reasonable — involves connection from access points to cabinets and from central facility to manhole(s) or other cable access
Ongoing (maintenance) cost	Reasonable — owner has full maintenance responsibility	High — lease costs almost always tied to general service rate increases. Agency must maintain connection described above
Maintenance responsibility	Clearcut — always borne by the owner	May be difficult to determine whether problems are the responsibility of lessor or lessee
Control of communication network	Excellent — owner is user and can fully control	Questionable — traffic requirements and limitations for 3002 channel may impede use
Design of communication network	Completely flexible since designer/owner starts from scratch	Subject to existing telephone company cable network which may not fit planned signal system layout
System expansion	If properly planned at the outset, additional intersections easily accommodated	Subject to cable availability in vicinity of proposed new signal installation(s)
Reliability	Excellent, with proper maintenance procedures	Good to poor — depends upon lease contract terms and level of owner's maintenance function

The designer must weigh the high capital costs for installation of a user-owned cable system against the sometimes unpredictable future plateau of rates for the leased-type system. For this reason, virtually all of the systems designed and installed over the past several years have employed user-owned wire-pair cables.

Coaxial Cable

Coaxial cable (sometimes abbreviated "coax") consists of a single inner conductor and an outer annular conductor (shield), whose center is coaxial with the center of the inner conductor. The annular space between the conductors is filled with a dielectric material selected for its electrical properties (insulation resistance, dielectric value, dielectric strength) and its mechanical properties (strength, lightness, and water absorption characteristics). The cable is specifically designed to obtain minimum signal losses, large signal information capacity, low signal interference susceptibility, and low signal leakage (*3*).

The primary cable mechanical parameters (inner-conductor, outer-diameter; outer-conductor, inner-diameter; and dieletric material) have been optimized to achieve the lowest signal loss per foot, with the result that the impedance of the most commonly used cable is 75 ohms (*3*).

A traffic control communications system employing coaxial cable as the transmission medium consists of coaxial cable and repeater amplifiers arranged as a tree network connecting a control-center communications unit with transceivers at each intersection. The cable and amplifiers have a wide radio-frequency bandwidth (5 MHz to 400 MHz), which can handle the traffic control communication requirement of any city, and can also accommodate many television channels at the same time, if required. The cable has low signal attenuation losses, while the repeater amplifiers have low noise levels and excellent signal linearity over a wide range of output levels. The repeater amplifiers are placed along the cable network at points where the signal has been attenuated to the minimum permissible level. By using appropriate filters and amplifiers at the repeater amplifier positions, the cable can carry signals in both directions simultaneously by dividing the total bandwidth into two parts, one for signals toward intersections, and one for signals from the intersections (a form of FDM) (*3*).

A coaxial cable system utilizes frequency-division multiplexing (FDM) and time-division multiplexing (TDM) to accommodate all of the traffic control signals on a single conductor. Signals being transmitted from the control center occupy one portion of the frequency spectrum, while the signals being received at the control center occupy a different portion of the available spectrum. TDM techniques are used to transfer information between the central unit and the intersections. The details of the TDM system (number of intersections, sampling rate, address code, security coding, and synchronization techniques) determine the total baseband bandwidth required. The baseband signal is frequency-translated to the desired area of the radio frequency spectrum. Additional intersection capability is achieved by duplication of the TDM system through translation of its baseband signal to a different area of the available spectrum (FDM). Thus, expansion can be accomplished by frequency assignment until the total spectrum is utilized (*3*).

Figures 8.13 and 8.14 graphically illustrate, respectively, the 2-way flow of data through central communications and intersection communication interface equipment.

Installation methods for coaxial cable are the same as those used for twisted-wire-pair cable: Underground in conduit, underground by direct burial, and aerial installation on existing or provided poles.

Owned vs. Shared Use. Coax cable is considered a broadband medium because it provides an extremely high capacity for data communications. To give some perspective, a Federal Highway Administration communication trade-off study equated one coax cable to 100,000 telephone wire pairs with respect to channel capacity (*3*). It is obvious that sufficient capacity exists to meet traffic signal system needs on a shared-cable basis, subject to establishing satisfactory working relationships and user agreements (*5*).

The equipment and installation costs of user-owned coaxial cable networks are similar to those of twisted-wire-pair networks. Additional costs are incurred for line (repeater) amplifiers plus their power sources and cabinets. Some cost advantage over twisted pair networks results from the fact that twisted pairs require extensive design and installation effort to identify, splice, or connect each wire at every intersection. Coax networks require that only a single coaxial cable and a trunkline tap be installed at each intersection. The cost of transceivers at the intersection is generally comparable to that of twisted-pair TDM units, but the front-end computer cost and the cost of programming it is usually higher than that of typical twisted-pair central communication units (*3*).

Cable TV Systems (CATV). The basic requirement for shared-use of CATV is that the system be duplex, i.e., it must be capable of sending signals in both directions over the cable. Many of the systems installed over the past few years are of the duplex type, making them viable candidates for the communication medium in traffic control systems.

A schematic of a typical cable TV system is shown in Figure 8.15. A description of some of the terms used within the cable TV industry follows:

- Headend — The control center for a cable TV system is generally located near the geographical center of the service area and sometimes includes the local programming studio and administrative offices. The satellite receiver, sometimes called an earth station, is a large outdoor disk antenna located at the headend. Large CATV systems may have multiple headends with one designated as the master, hence, the terms "master hub" and "subhub." These hubs may be interconnected by direct cable or by microwave communications (*5*).
- Subscriber network — A tree-shaped cable network which carries entertainment packages and other data to the household subscriber. Feeder cables connect this network to each subscriber. In duplex systems, it usually has limited capacity for returning information to the headend (*5*).
- Institutional network — A separate cable network for two-way communications to accommodate information return to the headend in support of security systems and viewer response systems. It is frequently used to provide special services to and between libraries, government centers, hospitals, and schools, and it is usually installed alongside the subscriber network at little additional cost (*5*).
- Downstream — All signals from the headend to the literally thousands of receivers are downstream signals (*5*).
- Upstream — Signals from any of the remote locations to the headend are upstream signals. Data interchange from one institution to another requires passing through the headend, as upstream and downstream signals on each side of the headend (*5*).
- Subsplit cable — A standard 5 to 400 MHz frequency range is dedicated for 35 or more downstream TV channels, plus FM and limited digital communication. This leaves only the 5 to 50 MHz range for upstream digital and video communications. The subsplit cable, which represents normal subscriber cable arrangement, is graphically depicted in Figure 8.16 (*5*).
- Channels — In CATV systems, the 5 to 400 MHz range generally is subdivided into 6 MHz increments or channels (*5*).

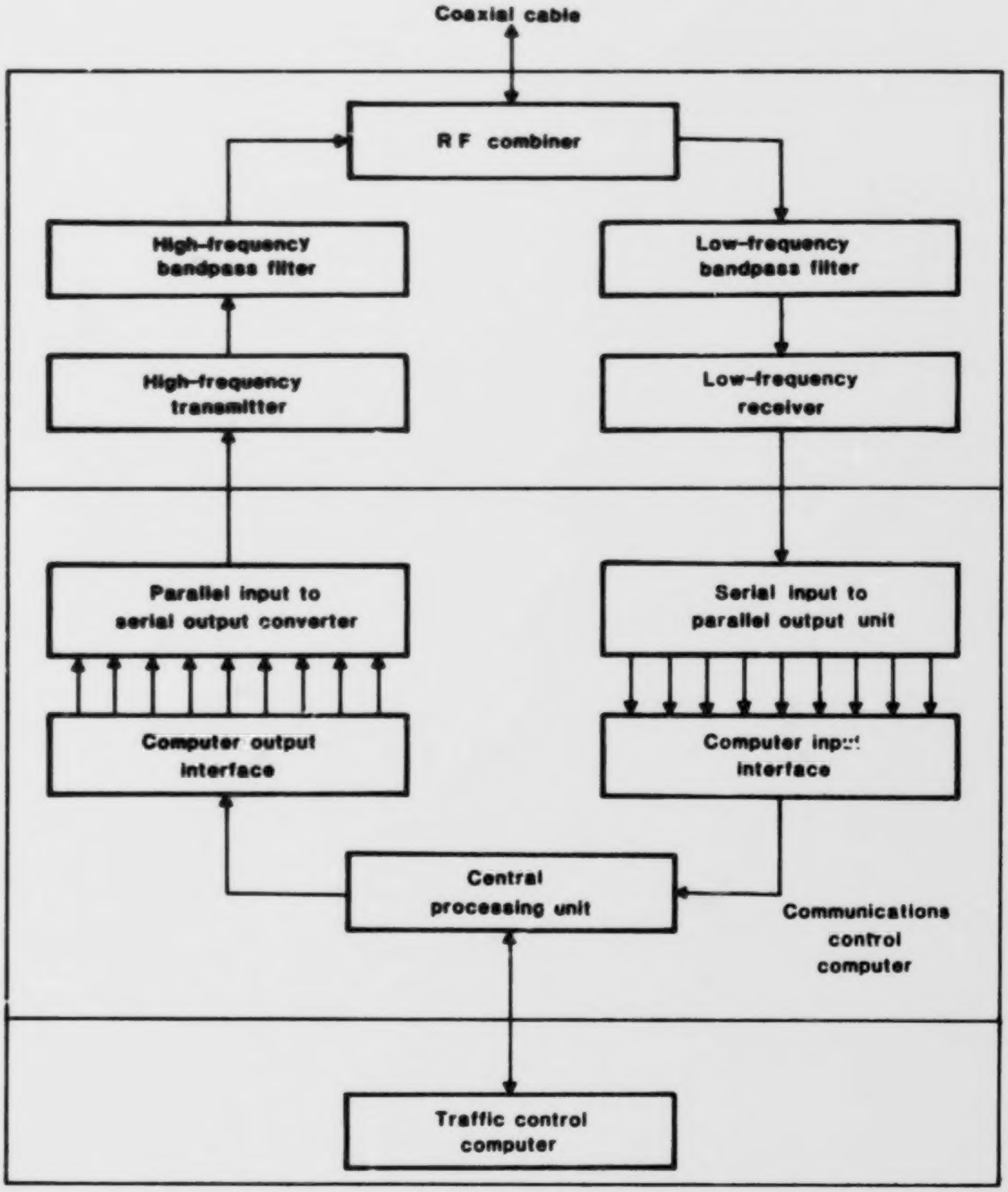
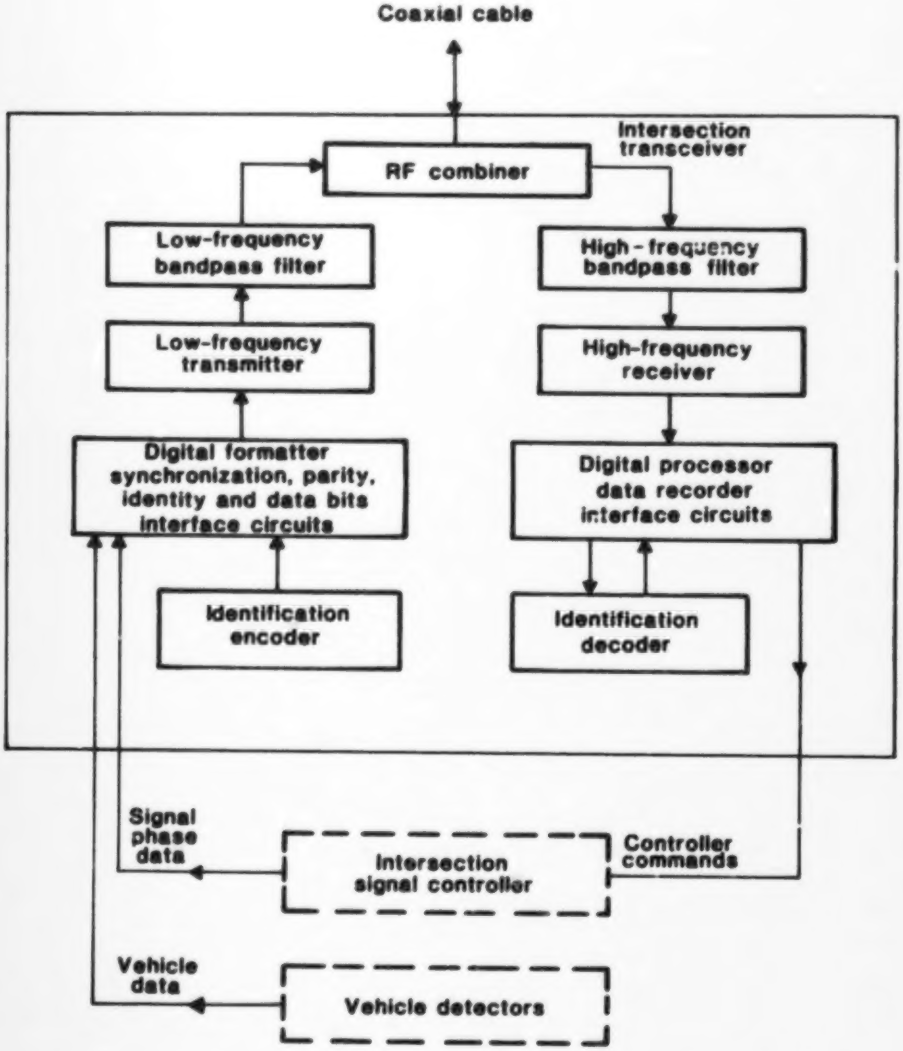

Coaxial cable
R F combiner
High-frequency bandpass filter
Low-frequency bandpass filter
High-frequency transmitter
Low-frequency receiver
Parallel input to serial output converter
Serial input to parallel output unit
Computer output interface
Computer input interface
Central processing unit
Communications control computer
Traffic control computer

Figure 8.13. Central control interface equipment for coaxial cable system

288



Coaxial cable
Intersection transceiver
RF combiner
Low-frequency bandpass filter
High-frequency bandpass filter
Low-frequency transmitter
High-frequency receiver
Digital formatter synchronization, parity, identity and data bits interface circuits
Digital processor data recorder interface circuits
Identification encoder
Identification decoder
Signal phase data
Intersection signal controller
Controller commands
Vehicle data
Vehicle detectors

Figure 8.14. Intersection control interface equipment for coaxial cable system

Source: Reference (*3*)

Any consideration of shared-use of a CATV network for traffic signal system communications should include the following points:

- Adequate frequency allocation for upstream and downstream channels for signal control uses
- System design compatibility for real-time, 2-way high-priority uses
- Assurance of cooperation by the franchise holder, and assistance for implementation of the communication links to local controllers cabinets and to the central signal control facility
- CATV cable routing and its proximity to signalized intersections
- Clarification of maintenance responsibility and expected response time for repair by franchise holder

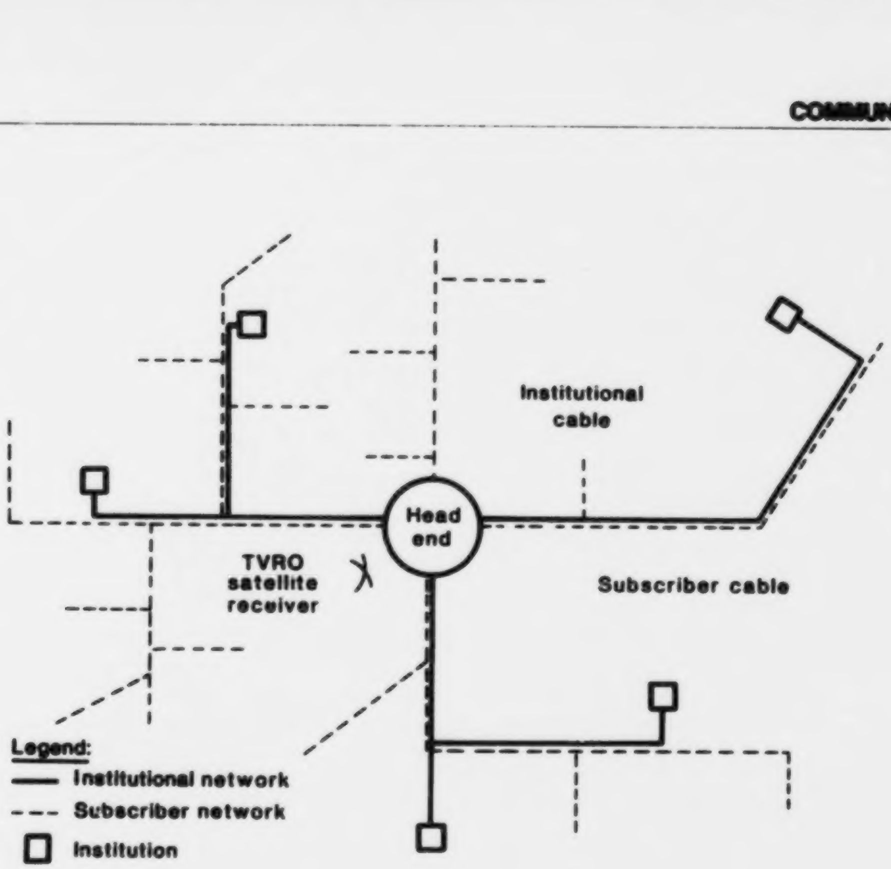


Figure 8.15. Typical cable television (CATV) layout

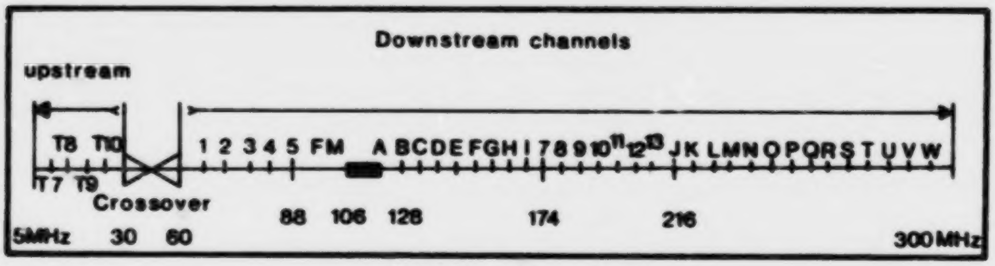
Source: Reference (*5*)

- Determination of lease costs and future trends of rates

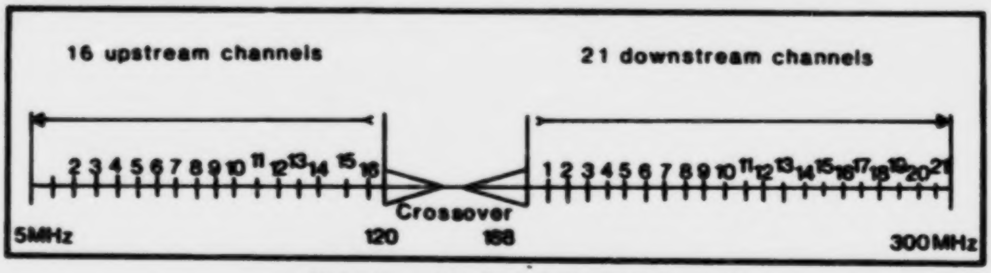
Regulatory aspects of coaxial cable communications are limited to control of any interference in such a system which could cause problems to other services. The interference radiation requirements of the CATV system must be observed as specified by the FCC rules given in the document, "Federal Communications Commission Rules and Regulations — Volume II, Part 76, Cable Television Service" (*3*). Obviously, when consideration is being given for possible use of part of a CATV system for communication purposes in a signal system, the traffic engineer or system designer should obtain from local controlling agencies and from the CATV franchise holder's representative, all applicable restrictions and industry practices related to system operation and access requirements. These factors must be analyzed very closely before leasing of part of the CATV system can be considered as a candidate for the communications tradeoff process.

Experiences. Dedicated coaxial cable for traffic control has been used successfully. Columbus, Ohio, has employed user-owned coax in an urban street traffic control system since 1976. In Overland Park, Kansas, a system is operating using the local CATV system on a lease basis. In Detroit, the Detroit Freeway Surveillance Control and Driver Information System (SCANDI) utilizes user-owned, off-the-shelf cable TV hardware and coaxial cable for 2-way broadband video and data communications (*5*).

The Overland Park experience in using leased CATV facilities as the system communication medium has produced few undesirable results. In 1979, during system implementation, difficulties in signal degradation were encountered. These problems were traced to the amplifier connection and field splicing methods used by the franchise holder. The upgrading of all connection and splice points proved to be the solution to the problem. A recent interview with the traffic operations engineer revealed that no other significant problems have occurred. The city's relationship with the CATV company regarding maintenance, lease rates, and general communication reliability is excellent. Communication failure rates are low, and usually are linked to lightning strikes to the overhead coax during thunderstorms.


Downstream channels
upstream
T8 T10
T7 T9
Crossover
1 2 3 4 5 FM A B C D E F G H I 7 8 9 10 11 12 13 J K L M N O P Q R S T U V W
5MHz
30
60
88
108
128
174
216
300MHz

Subsplit cable network



Midsplit cable (institutional network)

Figure 8.16. Cable television (CATV) channel splits

Source: Reference (5)

Since the Overland Park experience with shared-use coax for communications may not, however, be altogether typical, potential users must consider all points examined and should amply investigate all facets before making decisions.

Fiber-Optic Communication

The following description of fiber-optic communication for use in a traffic control system describes hardware which would be necessary to link master-unit-controlled intersections. At present, fiber-optic cable has not been used in a short-link application. Several factors, including fractional utilization of available bandwidth and the expensive transceivers required at each controlled intersection, have influenced decisions by potential users of this relatively new communications medium.

A fiber-optic data link is functionally the same as a data link using wire pairs or coaxial cable, except that the transmitter module converts electronic signals into optical signals. Similarly, on the receiving end of the data link, a module converts the modulated optical signals back to electronic signals. The fiber-optic transmission medium is an optical waveguide, which in the case of a single-fiber data channel, is quite analogous to a coaxial cable or, more accurately, to a cylindrical waveguide. The glass fiber is coated with a cladding of plastic or glass which has a different refractive index from the glass in the fiber itself. When these elements are properly designed, light rays entering the clad fiber will be reflected off the fiber wall so that they propagate along the inside of the fiber without escaping until they reach the end. By employing high-purity fused quartz in the fiber-optic cable manufacturing process, it is possible to use this medium for long-distance transmission (up to 16 mi) without need of re-amplification in repeater units (*3*).

Serial binary (on/off) modulation, which is the simplest technique for transmitting data over fiber-optic data links, is the method most commonly employed. The very large data handling ability of these data links (which can be greater than several hundred megabits per fiber) permits conversion of a large number of parallel inputs into a single serial data channel by multiplexing. The serial data is then converted back to parallel form at the receiver end of the fiber (*3*).

In a traffic signal system application with multiple intersections, the heart of a fiber-optic communication system is a bidirectional repeater (transceiver) which acts as the interface between the fiber-optic cable and the electronics at the control center and at the intersections.

Figure 8.17 shows a simplified layout of a fiber-optic data link repeater transceiver. Transmitter and receiver modules are interconnected via a fiber-optic star configuration, which combines the transmitter and receiver paths at each data link interface. As a repeater, the transceiver functions as follows: an optical data signal arriving from the upstream direction enters the optical receiver via Star-leg 4. There it is converted into an electronic signal which is amplified and coupled electrically to the transmitter input. The T2L driver is then used to modulate a light-emitting diode (LED) with pulsed modulation, usually in a serial binary code, thus converting the data pulses back into a modulated optical signal.

Fiber-optic Star-leg 2 then couples this energy into the downstream cable via fiber-optic connectors. Conversely, an optical data signal arriving from downstream is coupled to the receiver via fiber-optic Star-leg 3. As before, the receiver output is electrically connected to the transmitter which couples the amplified optical signal via Star-leg 1 to the upstream cable (*3*).

The above description of the operation of the repeater transceiver has been simplified for easier functional explanation. In practice, the transmitter actually has two separate T2L driver/transmitters, one for upstream and one for downstream transmissions. Also, on the downstream side of the transceiver, a trifurcated fiber-optic assembly is utilized to evenly-divide and couple up to three branch fiber-optic conductors. Thus, a practical, 2-way hookup scheme for downstream intersections is provided at each transceiver.

Fiber-optic cables are connected to transmitter/receiver modules with connectors of various types. The most common connector used is similar to standard coaxial cable connectors, and the most applicable for use in traffic signal systems is identified as an SMA connector. This connector is small and provides for precise mating of opto-electronic devices to the fiber-optic cable (*3*).

A fiber-optic cable can be installed underground in conduit or by the direct-burial method. For better cable protection, installation in conduit is preferred.

Experiences. At the present time, fiber-optic cable is being used for trunkline communications in the Los Angeles traffic signal system. It is also being utilized to tie the central computer facility to submaster units for 2-way transfer of data in the distributive-type hierarchical system. At present, it is the only known example of practical application of the fiber-optic medium for communication in signal systems in the United States.

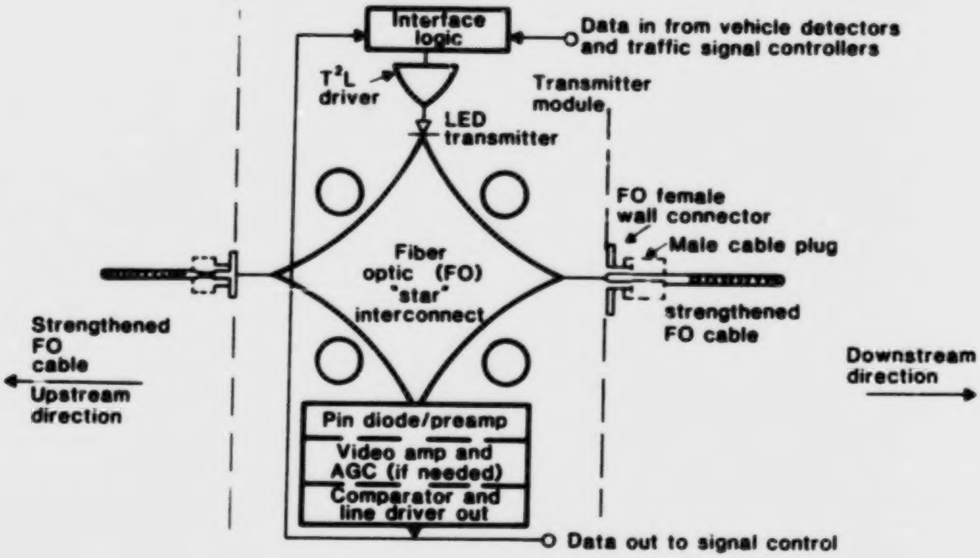

Interface logic
Data in from vehicle detectors and traffic signal controllers
T²L driver
Transmitter module
LED transmitter
FO female wall connector
Male cable plug
Fiber optic (FO) "star" interconnect
Strengthened FO cable
strengthened FO cable
Downstream direction
Upstream direction
Pin diode/preamp
Video amp and AGC (if needed)
Comparator and line driver out
Data out to signal control

Figure 8.17. Fiber-optic repeater transceiver

Source: Reference (*3*)

Air-Path Communication

Laser. Energy in the optical spectrum (usually visible but very near the infrared frequencies) can be used for transmission of data through the atmosphere. This type of transmission has become available in recent years through the development of injection-laser transmission diodes and light-sensitive reception diodes, similar to those used in fiber-optic transceivers. Figure 8.18 is a block diagram of a laser communications transceiver. A typical optical head/transceiver unit is constructed as a cast aluminum cylinder weighing about seven pounds (*3*).

Laser equipment has been used in an experimental traffic control communication system. The system is comprised of pole-mounted, single or multiple optical unit/transceivers at each intersection, facing their upstream and downstream counterparts, plus a microcomputer at each location for data processing. Thus each transceiver acts as a repeater for data transmission in each direction and also communicates with the local controller unit. Figure 8.19 is a schematic of this scheme (*3*).

The range of the optical heads is limited to about 3,000 ft when high-power injection-laser diodes are used for transmission. With the exception of heavy fog or other atmospheric conditions which severely restrict visibility, weather conditions have had little effect on the laser communications system. However, some unique aspects of the system which a potential user must address are as follows:

- Extreme rigidity must be maintained in head support members, and the pole structures on which they are mounted. Head deflection must be virtually nonexistent. Thermal expansion or contraction of head support members can also cause unwanted deflection of the optical heads.
- Line-of-sight clear paths must be maintained between transceiver units.
- It must be assured that, at peak power, the laser beam is within eye-safety certification requirements (*3*).

Microwave. The microwave communication medium has generally not found acceptance for use in traffic signal control systems. Among the concerns in the use of microwave are the following:

- The medium is suitable, practically speaking, only for simplex operations
- Line-of-sight clear paths are required between the transmitter and receivers.
- Ignition noise in close proximity to receivers causes signal interference problems.
- Certain atmospheric conditions and the physical layout of the taller buildings (in an urban environment) cause attenuation (loss) of signal power.

Radio waves at frequencies on the order of 1,000 MHz, and above, have many of the characteristics of light waves, and certain optical principles are useful in describing their propagations. Direct, line-of-sight, optical paths are applicable to microwave transmission theory, and are similar to those required in laser communication(*3*).

From an abstract point of view, a radio communication system can be thought of in terms of its ability to transmit information at a suitable rate, with acceptable fidelity, while contending with the electromagnetic

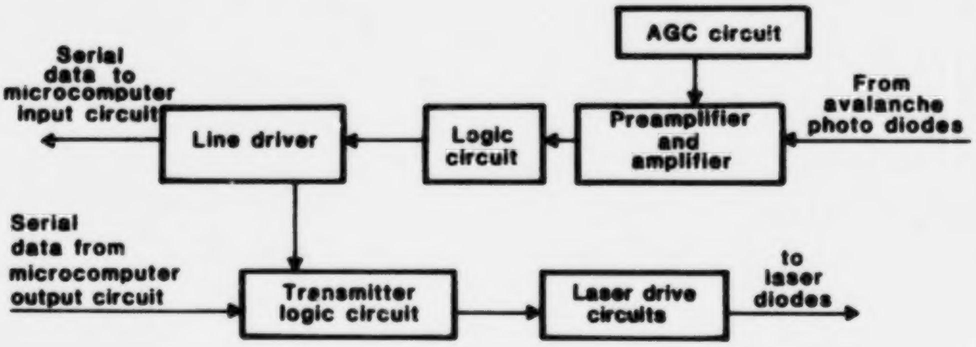

AGC circuit
Serial data to microcomputer input circuit
From avalanche photo diodes
Line driver
Logic circuit
Preamplifier and amplifier
Serial data from microcomputer output circuit
Transmitter logic circuit
Laser drive circuits
to laser diodes

Figure 8.18. Block diagram of laser transceiver unit

Source: Reference (*3*)

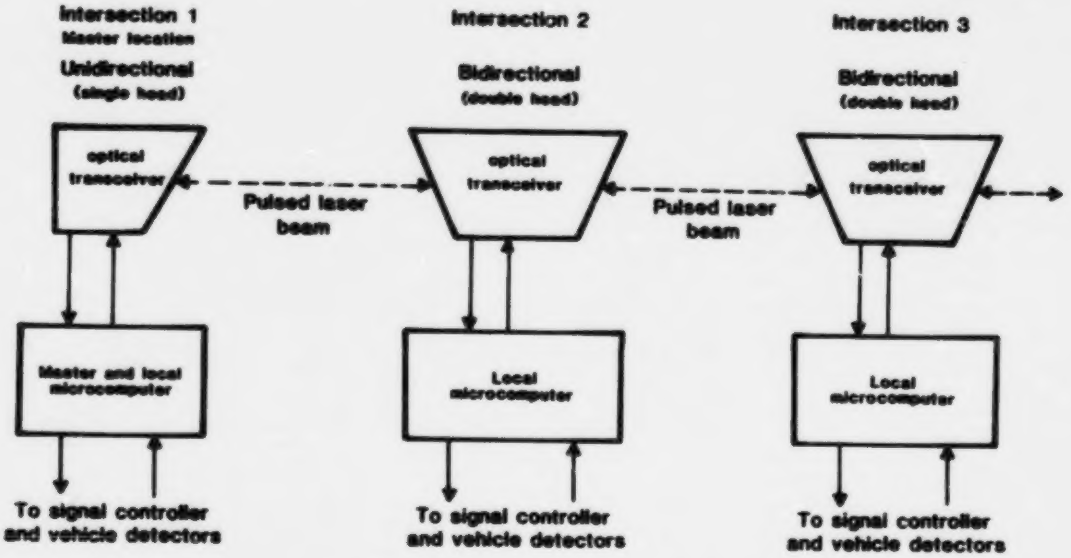

Intersection 1
Master location
Unidirectional
(single head)
optical transceiver
Pulsed laser beam
Master and local microcomputer
To signal controller and vehicle detectors
Intersection 2
Bidirectional
(double head)
optical transceiver
Local microcomputer
To signal controller and vehicle detectors
Pulsed laser beam
Intersection 3
Bidirectional
(double head)
optical transceiver
Local microcomputer
To signal controller and vehicle detectors

Figure 8.19 Laser communications system

Source: Reference (*3*)

environment associated with terminal locations, the allocated frequency spectrum, and the limitations imposed by the equipment available. Before serious consideration is given to use of such a communication system, a complete analysis must be conducted on the following factors:

- Path characteristics
- Equipment characteristics
- Transmitted message requirements
- Operation and maintenance requirements of system (*3*)

8.4 COMMUNICATION SYSTEM PLANNING AND EVALUATION

Previous discussion has pointed out a variety of alternatives available to the communication system planner. Under some circumstances, choices are relatively clear-cut; others must be made as compromises between competing alternatives. Good communication system planning involves many considerations, including the following:

- Careful study of present and future control system configuration, size, and operational and surveillance capabilities
- Analysis of both typical and worst-case transmission requirements
- Systematic selection process that yields a communication system which fits into the total system picture

The following discussion considers some key factors in communications planning and evaluation, and their practical application. It should be noted that the traffic engineer, when faced with the planning and evaluation process, can usually obtain good assistance from vendors and/or manufacturers of communication equipment.

Selecting Transmission Rates

The physical communication links in a traffic control system are more or less dictated by geographical considerations. Locations of local signal/control equipment are fixed, and links must be provided between each local controller and its submaster and/or the central facility. Since the data rate requirement in each link is not so rigid, this parameter varies in accordance with such aspects as the following:

- Complexity of the local controller-oriented 2-way data, such as the following:
    - ▫ Control commands flowing to the intersection
    - ▫ Status information returned to submaster or to central

  - System detector and/or detector count data returned to submaster or central
  - Additional data needed for error checking and other communication housekeeping

- The number of system intersections (existing and future) on each multidrop line

Linkage planning, then must begin with a careful analysis of data rate requirements per intersection, which, when taken together for the entire link, will produce an accurate prediction of the maximum bit rate required in each channel. Once the analysis has been made, the types of linkages can be specified.

The key concern in specifying the links is in the tuning of the entire communications network. This implies balancing communications requirements throughout the system in order for data to flow smoothly and regularly from unit to unit. A common error in planning of this type is the inadvertent inclusion of a constrictive link — that is, a key link whose data-carrying capacity is inadequate to carry the maximum data transmission rate required by the equipment in the system — beyond that link.

Requirements for Communication Link Quality

Transmission link quality can be measured in several ways, two of which are as follows:

- Envelope delay — This type refers to the variation in delay seen by signals at the different frequencies within the allowable bandwidth of the link. If the delays are not relatively balanced throughout the bandwidth, some signal frequencies will propagate through the channel link more rapidly than others. This action will then distort the received signals and may cause the receiver to make errors. Conditioning can reduce transmission errors by correcting imbalance in a channel's delay characteristics. It can also widen the bandwidth of the channel, as well as equalizing signal attenuation.

- Error rate — The error rate is a parameter usually measured over a closed path by using a wrap test. Here, a known data word is sent over the link, received, and retransmitted over a parallel link, thus wrapping back to the original transmitter. The output word is then compared with the original data word and any errors noted. The process can be repeated for a known period of time, allowing the error rate over the channel to be measured.

Communication link quality varies with the previously described types of communication media, and, as indicated above, is indirectly tied to the available usable bandwidth of the communication medium selected.

Requirements for Communication Link Reliability

All equipment is subject to accident or failure, and communication equipment is no exception. A particular link may be cut by a traffic accident, a ditch-digging operation, or other occurrence. Electrical component failure may cause a link to become totally inoperative, or, what is more troublesome, to be intermittently error-prone. If a key link should fail, the integrity of an entire traffic control system could be threatened. The potential effects of a broken link must be considered as early as the system planning stage. Truly vital links may necessitate two or more full operational channels, so that back-up capability is readily available. Also, all key remote equipment should have sufficient stand-alone operational capability. In this way, useful functioning would continue even if the link between the local controller unit(s) and the submaster or control center were inoperative.

The possibility of a link failure may make it desirable to distribute the control and decision-making capacity throughout the system. Distributed, closed-loop systems, as discussed in Chapter 7 of this Handbook, are examples of this concept.

If a full- or half-duplex operation is used, the operation of each link and receiving unit should be monitored by requests for return transmission of status. Requests for retransmission should be logged, so that noisy or error-prone channels can be identified.

Other maintenance aids, such as voice communication between signal installations and with the central facility, should be considered during the system planning stage. A suitable preventive-maintenance program should also be planned to keep the communication system in peak operating condition.

Trade-Off among Communication Alternatives

Once the initial system design phase is completed, the type of communication system to use needs to be determined. Because communications system is the most expensive element to install, the proper selection of a communication medium (or media) must be made during the final system design and implementation phases (6).

Function-specific factors for the proposed communication system, such as those previously described, must be satisfied by the candidate media assembled for trade-off considerations. Features of the control system which influence communication requirements are the function-specific factors; the principal ones being the number of functions and the data rate with which they must be transmitted. Some other traffic control system features which influence the choice of the communication medium to be used include the following:

- Quantity of vehicle surveillance data and controller monitoring data transmitted to a central or master controller
- Quantity of command data transmitted from central or master to the roadside cabinet
- Quantity of data required for special functions (*3*)

Locality-specific factors must also be satisfied by the candidate media assembled for considerations. The factors are those physical features that are unique to the locale, and include the following:

- Number and location of field cabinets, (and sub- or area-masters, if used), and location of the control center, all of which affect lengths of transmission paths and number of communications units
- Complexity of local controller units and number of vehicle detectors
- Availability and condition of existing conduit
- Number of usable existing local controllers
- Location of other utility equipment that may interfere with installation
- Skill levels of personnel who will be involved in future maintenance activities
- Desired degree of future systems expansion

Directly influencing the candidate media for communications is the type of system processing architecture to be employed. Transmission rates required by the above listed functions, the type of communication method used, and the system architecture are interrelated (*3*).

System processing architecture types are generally categorized as follows:

- A centralized type of architecture, in which the communication subsystem links the vehicle detectors and traffic controllers directly to the computer at the control center, as shown in the simplified block diagram of Figure 8.20. The communication subsystem consists of the selected transmission medium and appropriate communications equipment located at each intersection and at the control center. This type architecture provides the greatest degree of time concurrence between the command, or the street event and its related received data.
- A distributed processing type of architecture, in which the communications subsystem links the system master with local intersection controller units, as shown in Figures 8.21 and 8.22. In the hierarchical type, distributed-processing scheme (Figure 8.21), the central or master computer provides area control timing plans to local controller units. For the network-type system (Figure 8.22), each submaster controller unit is usually located at an intersection, and is connected by the communication subsystem to a group of local controller units. Thus, under this scheme, the submaster units may require additional limited inter-communications (such as dial-up links) to a control center for monitoring data collection, or for timing-pattern updating purposes. In a distributed processing type system the local computers process much of the data from vehicle detectors and controllers, thereby decreasing the amount of data that must be transmitted between computer and local controller in a comparably sized central-type system. In this type of architecture, real-time status data and individual vehicle presence data are not transmitted directly to the control center. Rather, data are processed and stored, and subsequently transmitted on an appropriately scheduled basis (or on demand) to the central facility (*3*).

Thus, if individual vehicle presence is required at the control center accurately in time, or if traffic signals must change instantly in response to central or master computer outputs, then a central type of architecture will probably be selected and the communications method selected will have to be capable of transmitting data at relatively high rates of speed (*3*).

If real-time transmission of data is not required, then one of the distributed processing architectures (hierarchical or network) may be chosen, and the data rates (and, therefore, the bandwidths required of the medium) may be reduced accordingly. Consequently, the communication method selected for this type of architecture will be influenced more by the locality-specific factors than by the function-specific factors (*3*).

Once the various constraints have been used to bound the system architecture and control capabilities, a set of candidate communications media may be selected. The next step is to determine the relative merits of the various candidates with respect to their ability to perform all functions required by the traffic control system. Usually,

296

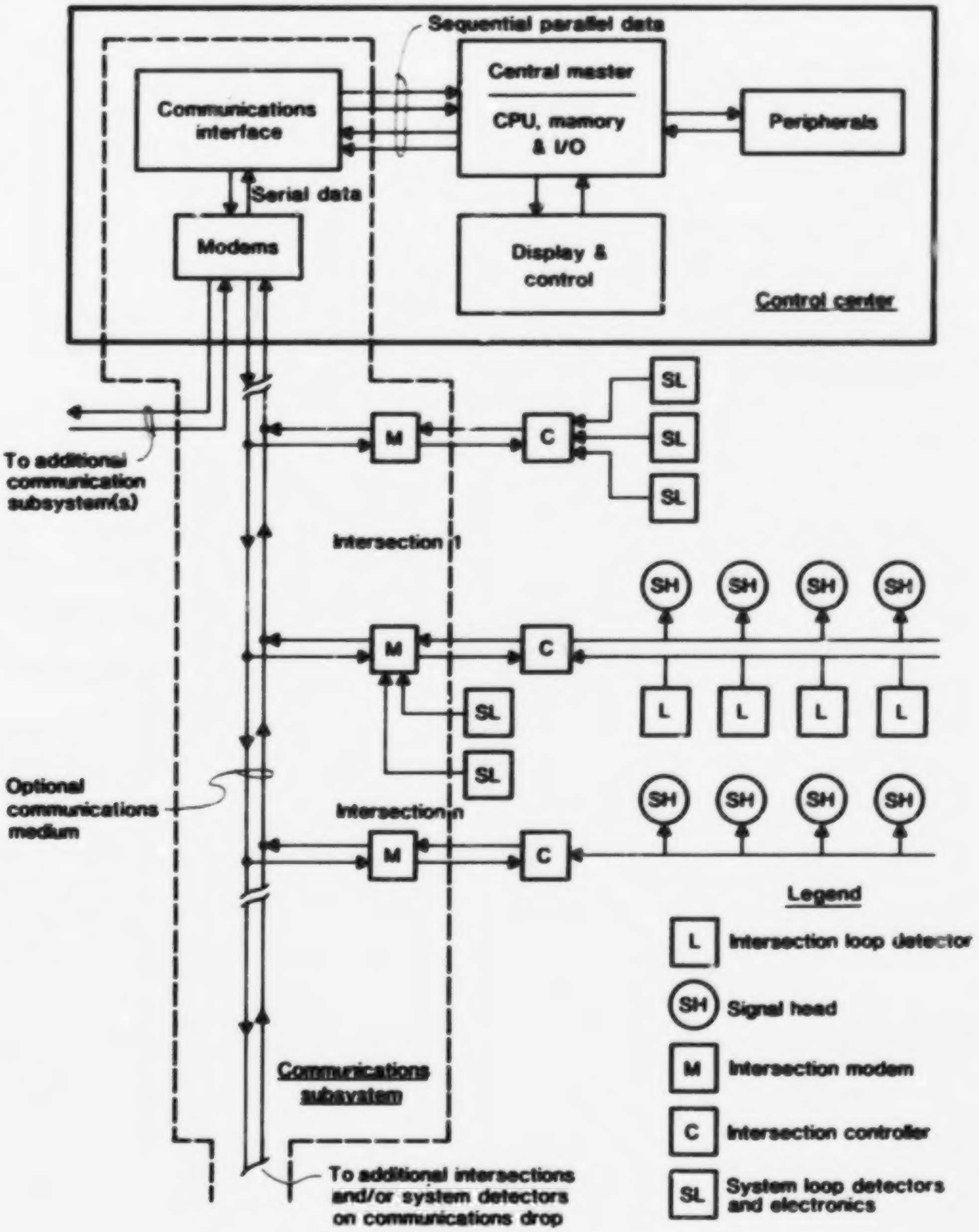

Sequential parallel data
Communications interface
Central master
CPU, memory & I/O
Peripherals
Serial data
Modems
Display & control
Control center
To additional communication subsystem(s)
SL
SL
SL
M
C
Intersection 1
SH
SH
SH
SH
M
C
SL
SL
L
L
L
L
Optional communications medium
Intersection n
SH
SH
SH
SH
M
C
Communications subsystem
To additional intersections and/or system detectors on communications drop
Legend
L Intersection loop detector
SH Signal head
M Intersection modem
C Intersection controller
SL System loop detectors and electronics

Figure 8.20. Central-type architecture block diagram

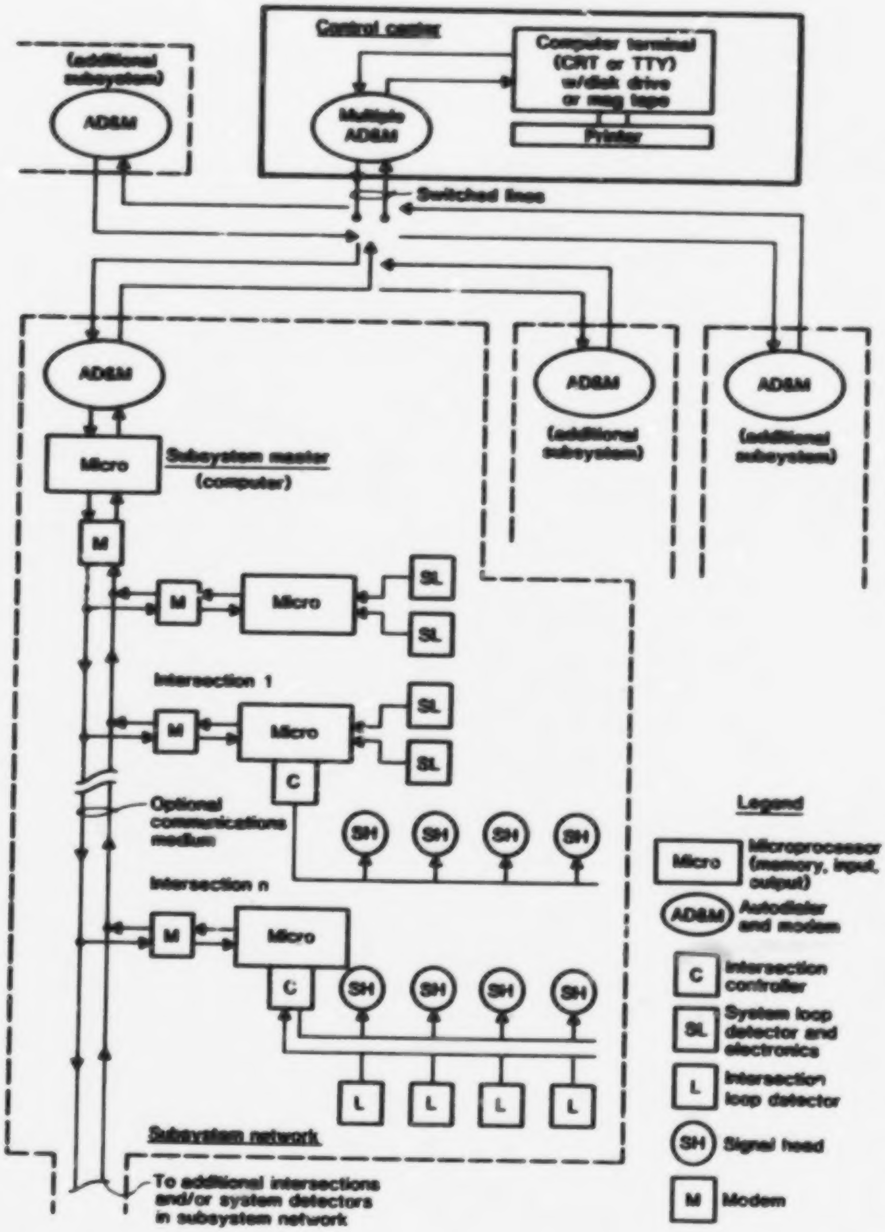

Control center
Computer terminal (CRT or TTY) w/disk drive or mag tape
Printer
Multiple AD&M
(additional subsystem)
AD&M
Switched lines
AD&M
AD&M
(additional subsystem)
AD&M
(additional subsystem)
Micro
Subsystem master (computer)
M
M
Micro
SL
SL
Intersection 1
M
Micro
SL
SL
C
Optional communications medium
SH
SH
SH
SH
Intersection n
M
Micro
C
SH
SH
SH
SH
L
L
L
L
Subsystem network
To additional intersections and/or system detectors in subsystem network
Legend
Micro
Microprocessor (memory, input, output)
AD&M
Autodialer and modem
C
Intersection controller
SL
System loop detector and electronics
L
Intersection loop detector
SH
Signal head
M
Modem

Figure 8.21. Hierarchical-type distributed processing architecture

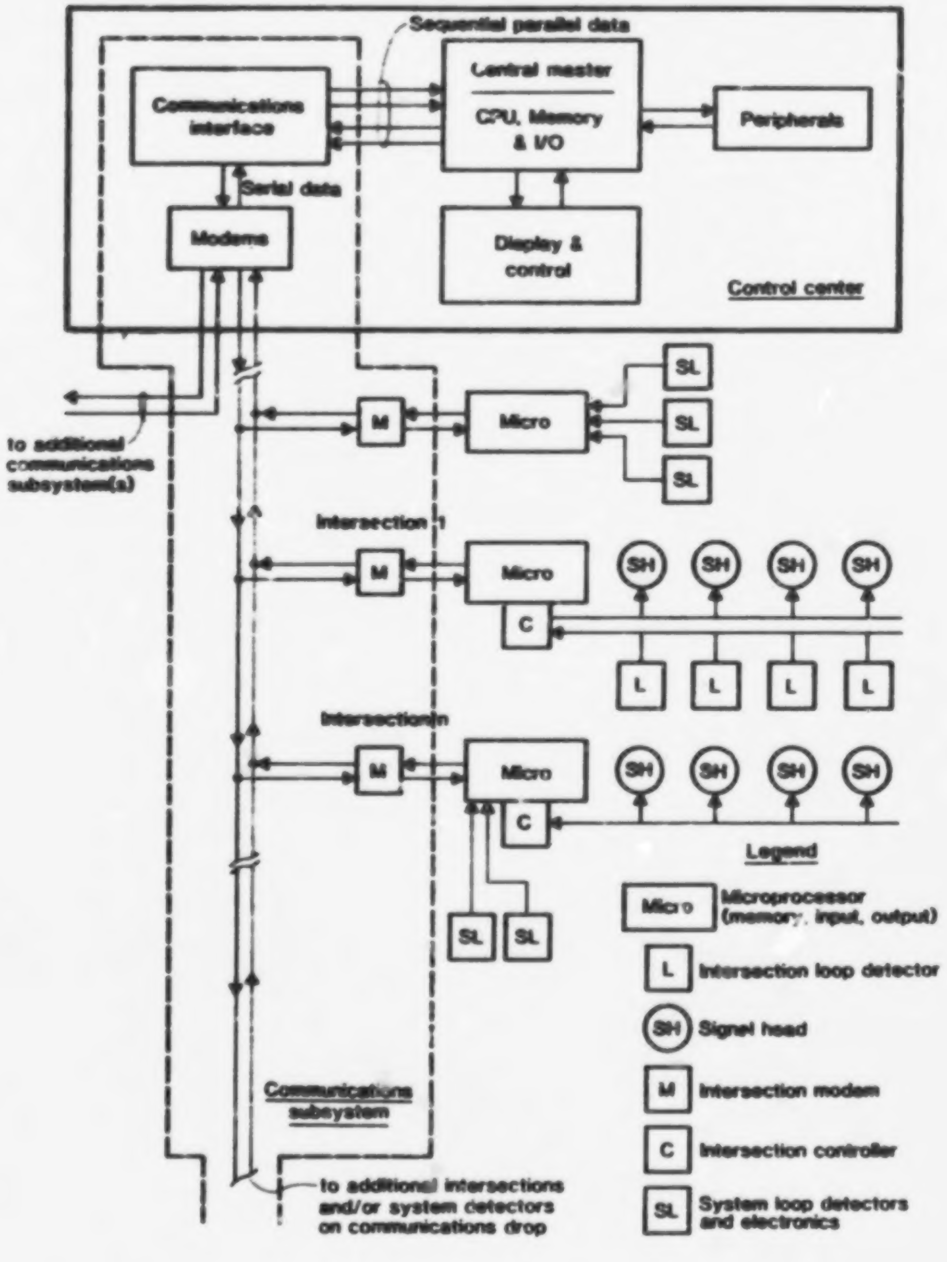

Sequential parallel data
Central master
CPU, Memory & I/O
Communications interface
Peripherals
Serial data
Modems
Display & control
Control center
to additional communications subsystem(s)
SL
SL
SL
M
Micro
Intersection 1
M
Micro
C
SH
SH
SH
SH
L
L
L
L
Intersection n
M
Micro
C
SH
SH
SH
SH
SL
SL
Communications subsystem
to additional intersections and/or system detectors on communications drop
Legend
Micro Microprocessor (memory, input, output)
L Intersection loop detector
SH Signal head
M Intersection modem
C Intersection controller
SL System loop detectors and electronics

Figure 8.22. Network-type distributed processing architecture

299

the results of such an analysis will show that all candidates considered are capable of meeting system requirements on a nearly equal basis Generally, most communications system employing proven techniques will meet the functional requirements of the control system (*3*).

Utility/Cost Analysis

The next step in evaluation of the candidate systems, the utility/cost analysis, is a comparison of the candidate's ability to satisfy communications utility measures.

The utility/cost method is an approach which allows a means for assessing all of the benefits of a candidate system, regardless of whether or not they are dollar-quantifiable. This subjective method relies heavily on sound judgment, and represents a comprehensive examination of the problem which affords the opportunity for the inclusion of many factors which are often ignored (*3*).

The utility/cost approach begins with the selection of a utility model. The model includes a number of system attributes, or utility measures. These utility measures describe the properties which the system should have in order to fulfill its objective which, in this case, is to transmit data to and from the field. The utility measures are then ranked and weighted, with this list constituting an example utility model as shown in Table 8.2. It should be noted that the weights selected are representative of a typical system (refer to Chapter 10 for a discussion of utility/cost) and would be manually adjusted by the user to suit his particular needs. Also, the utility measures may be added and/or deleted by the user. It should be noted that, in Table 8.2, separate columns of weighted values for each of three system architectures (central, hierarchical, and network) have been entered (*3*).

To illustrate a practical application of a utility/cost analysis, seven candidate communications systems which are assumed, are listed as follows:

- FDM-leased telephone-paired cable
- FDM-owned telephone-paired cable
- TDM-leased telephone-paired cable
- TDM-owned telephone-paired cable
- Coaxial cable
- Fiber-optic cable
- Air-path optics (*3*)

These candidates were then related to the three system architectures in the following way:

Architecture	Candidate System
Central	FDM-leased or owned TDM-leased or owned Fiber optics Coaxial
Hierarchical	TDM-leased or owned Air-path optics
Network	TDM-leased Air-path optics

Compliance factors for each of the candidate systems are then determined and assigned, as shown in Table 8.3. These factors, the values of which range between 0 and 10, reflect how well the candidate satisfies the communication requirements. A compliance factor of 0 means the candidate cannot accomplish requirements, and one of 10 means the requirement is totally satisfied (*3*).

The candidate system utilities are next calculated by multiplying the system weight value (from Table 8.2) by the compliance factor for each candidate (from Table 8.3). A summary of these calculations is shown in Table 8.4. Also shown in Table 8.4 are candidate system costs, which are expressed in terms of present worth cost of ownership, i.e., the sum of initial costs and the present worth of yearly maintenance and operation costs over the candidate system lifetime (*3*).

As shown in Table 8.4, each candidate system utility total is divided by the candidate system cost resulting in respective utility/cost ratios for each candidate.

As noted earlier, these examples are intended for illustrative purposes only. Because costs and utility values are highly sensitive to the particular assumptions made for these examples, the results should not be used as an indication of relative merit for the communication media examined.

The reader desiring more detail on the procedures for a utility/cost analysis of candidate communications systems is referred to *A Communications Trade-Off Study for Computerized Traffic Control* (*3*).

8.5 ADDITIONAL INFORMATION SOURCES

The material presented in this chapter is intended to familiarize the reader with the broad aspects of communications systems as they impact traffic control. It is expected that additional information on specific aspects of current technology in the field may be desired. The

Table 8.2. System weights

Utility Measure	Central	Hierarchical	Network
Reliability	28	28	28
Maintainability	23	23	23
Installation ease	16	15	14
Invulnerability to damage	9	10	10
Procurement ease	9	9	9
System expansion ease	6	8	10
Monitoring capability	9	7	6
	100	100	100

Source: Reference (*3*)

Table 8.3. Compliance factors for candidate systems

	Central						Hierarchical			Network	
	FDM		TDM		Fiber		TDM		Air-Path	TDM	Air-Path
Utility Measure	Leased	Owned	Leased	Owned	Optics	Coax	Leased	Owned	Optics	Leased	Optics
Reliability	5	8	4	8	9	8	5	8	7	5	7
Maintainability	8	6	7	5	7	8	8	6	7	8	7
Installation ease	8	7	7	6	7	9	7	6	8	7	8
Invulnerability to damage	8	8	8	8	7	7	8	8	7	8	7
Procurement ease	9	9	8	8	6	7	8	8	4	8	4
System expansion ease	7	5	6	5	8	8	6	5	8	6	8
Monitoring capability	5	5	9	9	9	9	9	9	9	9	9

Source: Reference (*3*)

following publications are listed by subject area for the reader's convenience:

Data Communication

- *The Communications Handbook, 1981.* Microdata Corporation, 17481 Red Hill Avenue, Irvine, California 92705, 1981.
- *Averbach's Guide to Data Communications.* Averbach Information, Inc., 121 North Broad Street, Philadelphia, Pennsylvania, 19107. (Revised annually.)
- *Modern Data Communications: Concepts, Language, Media.* Hayden Book Company, Inc., New York, 1971.

Coaxial Cable Communication (CATV)

- "CATV Systems — Design Philosophy and Performance Criteria as the Basis for Specifying Equipment Components." *IEEE Transactions on Broadcasting*, April 1967.

Table 8.4. Candidate system utilities

Utility Measure	Central	Hierarchical	Network	Central-Type System						Hierarchical			Network	
				TDM		FDM		Fiber Optics	Coax	TDM		Air-Path Optics	TDM	Air-Path Optics
				Leased	Owned	Leased	Owned			Leased	Owned			
				*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.	*C.F. Util.
Reliability	28	28	28	5 140	8 224	4 112	8 224	9 252	8 224	5 140	8 224	7 196	5 140	7 196
Maintainability	23	23	23	8 184	6 138	7 161	5 115	7 161	8 184	8 184	6 138	7 161	8 184	7 161
Installation ease	16	155	14	8 128	7 112	7 112	6 96	7 112	9 114	7 105	6 90	8 120	7 98	8 112
Invulnerability to damage	9	10	10	8 72	8 72	8 72	8 72	7 63	7 63	8 80	8 80	7 70	8 80	7 70
Procurement ease	9	9	9	9 81	9 81	8 72	8 72	6 54	7 63	8 72	8 72	4 36	8 72	4 36
System expansion ease	6	8	10	7 42	5 30	6 36	5 30	8 48	8 48	6 48	5 40	8 64	6 60	8 80
Monitoring capability	9	7	6	5 45	5 45	9 81	9 81	9 81	9 81	9 63	9 63	9 63	9 54	9 54
Utility totals				692	702	464	690	771	807	692	707	710	688	709
Costs ($K)				1086	1252	904	1023	1106	1245	110	290	72	234	210
U/C ratio				.64	.56	.71	.67	.70	.65	6.29	2.43	9.86	2.94	3.38

* Compliance factor (from Table 8.3)

Source: Reference (*3*)

- "Design and Construction of CATV Systems." RCA, Community Television System Division.

Air-Path Communication

- "Optical Communications — A Decade of Preparations." *Proceedings of IEEE*, October 1970, pp. 1410-1418.
- *Laser Communications Systems*. John Wiley and Sons, New York, 1969.

Fiber-Optic Communication

- Eppes, T. A.; J. E. Goell; and Kao. "Use Optical Fibers for Long-Range Data Communications." *Electronic Design*, Vol. 8, April 12, 1976.
- Kasiewicz, A. B. "Communicating with Light." *Electronic Products*, November 1976.
- "Fiber Optics for All Environments." *Laser Focus*, August 1977.
- Stier, R., and R. Ohlhaber. "Fiber Optics or Electronic Cable?" *The Industrial and Process Control Magazine*, July 1984.

The list of content references which follows for the chapter also contains sources of additional information on communications in traffic control.

REFERENCES

1. "The PR System of Traffic Control." Bulletin E-226, Automatic Signal Division, Eastern Industries, Norwalk, Connecticut, 1957.
2. PRC Voorhees, "Computer Controlled Traffic Signal Systems." Report No. FHWA-IP-82-21, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1982.
3. Sperry Systems Management. "A Communications Trade-Off Study for Computerized Traffic Control." Report No. FHWA-RD-78-85, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1978.

302

BEST COPY AVAILABLE

4. Davey, J. R. "Modems, Computer Communications." IEEE Press, 1975.
5. Wilshire, Roy L. "Cable TV in Your Signal System Future." *ITE Journal*, October 1981.
6. "Developments in Traffic Signal Systems." Circular Number 282. Transportation Research Board, National Research Council, Washington, D.C., 1984.

303

9. DRIVER INFORMATION SYSTEMS

CONTENTS

Section | *Page*

9.1 INTRODUCTION 9.3

9.2 STATIC SIGNS 9.3

9.3 DIAGRAMMATIC SIGNS 9.4

9.4 CHANGEABLE MESSAGE SIGNS (CMS) 9.4
- CMS Display Types 9.6
- Mechanical 9.6
  - *Foldout Signs* 9.6
  - *Scroll Signs* 9.6
  - *Rotating Drum Signs* 9.7
- Light Source 9.7
  - *Neon Signs* 9.7
  - *Fiber-Optic Signs* 9.7
  - *Lamp Matrix Signs* 9.7
- Electromechanical 9.9
  - *Electromagnetic Disc Matrix Signs* 9.9
  - *Electromechanical Flap Matrix Signs* 9.11
  - *Tri-Color Signs* 9.11

9.5 TRANSPORTABLE SIGNS 9.11

9.6 HIGHWAY ADVISORY RADIO (HAR) 9.13
- Vertical Antenna HAR Systems 9.13
- Induction Cable Antenna HAR Systems 9.14
- HAR Experience 9.14
  - *Examples of Existing Systems* 9.17
- Automatic Highway Advisory Radio (AHAR) 9.18

9.7 MOTORIST AID SYSTEMS 9.18
- Call Box and Emergency Telephone Systems 9.18

9.8 CITIZEN BAND (CB) RADIO 9.20
- Broad Emergency Assistance Radio (BEAR) System 9.20
- Citizen Band Automatic Interconnect Digital System (CB/Aids) 9.21

9.9 COMMERCIAL RADIOS 9.22

9.10 CELLULAR MOBILE PHONE SYSTEM 9.22

Section *Page*

9.11 DESIGN GUIDE 9.23

9.12 TRANSPORTATION MANAGEMENT CENTER 9.23

9.13 LANE-USE CONTROL SIGNALS 9.25

REFERENCES 9.25

9. DRIVER INFORMATION SYSTEMS

9.1 INTRODUCTION

The highway transportation system involves three major elements: (1) the vehicle, (2) the roadway, and (3) the driver. The most complex of the three elements in the system is the driver, who is also the one element which is most prone to failure. A majority of these failures are due to errors in perception, or information processing, often the result of inappropriate information, lack of information, or simply overlooking available information.

To provide more adequate information and communication to the driver, concerning the roadway, the traffic engineer utilizes driver information systems such as traffic and lane control signals, traffic signs, pavement markings, delineators, telephone systems, and commercial radio.

Driver information is essential for the roadway system to operate efficiently and safely. Driver information systems have already been discussed earlier in Chapters 3 and 4 on control concepts for urban streets and freeways. In the present chapter, only a brief summary discussion will be needed to consolidate and identify types of hardware associated with driver information systems.

The major visual techniques for conveying driver information include the following:

- External
    - Signals
    - Static signs
    - Changeable message signs
    - Transportable signs
    - Pavement markings
- Internal
    - In-vehicle displays

Major audio techniques include the following:

- External
    - Warning signals
    - Public-address systems
    - Telephones
- Internal
    - Commercial radio
    - Low-power radio

Driver information systems are used in mainline control to advise motorists of freeway conditions in order that appropriate action can be taken by the driver to enhance the efficiency and safety of traffic operations. The traffic engineer's philosophy is to inform the driver of impending conditions with up-to-date information. With this information, the driver is capable of deciding what actions should be taken — i.e., whether to continue on the planned route with the knowledge of the problem ahead or to divert to an alternate route to avoid the problem.

The objective of this chapter will be to identify typical hardware associated with the various visual and audio techniques.

9.2 STATIC SIGNS

The three basic types of static signs include the following:

- Regulatory signs
- Warning signs
- Guide signs

Table 9.1 illustrates the intended use of each type and provides some examples. The *Manual on Uniform Traffic Control Devices* (MUTCD) (*2*) contains standards for the three types of static signs. This section will only describe the use of static signs to warn drivers of special freeway problems, such as a closed lane, congestion, or a particularly hazardous condition because of inclement weather.

Static signs are single-message signs, i.e., capable of conveying only one message. Single-message displays are most useful when a situation is recurrent and the same

Table 9.1. Sign types and uses

Sign Type	Intended Use	Typical Uses
Regulatory	To inform motorists of traffic laws and regulations which apply at definite locations and at specific times	• Intersection control • Definition of right-of-way • Speed limits • Turning movement control • Pedestrian control • Exclusions and prohibitions • Parking control and limits • Regulations for maintenance and construction
Warning	To warn motorists of unusual or potentially hazardous condition(s) on or adjacent to a street or highway	• Horizontal and vertical alignment • School areas • Crossings and entrances to streets, highways, and freeways • Intersection areas • Road construction and maintenance
Guide	To provide simple and specific information to aid motorists in reaching their destination	• Route markings • Destination • Information • General services • Parks and recreational information

Source: Reference (*1*)

driver response is desired each time the sign is used. Therefore, static signs can be used at locations where a hazard is well-defined and occurs periodically. However, these signs are limited in the type of information that can be displayed. For example, static signs cannot display distances susceptible to change (accident location, distance to end of queue, etc.), or times susceptible to change (delay information, travel times).

A common example of a static sign used to warn the driver of slow or stopped traffic is shown in Figure 9.1. Flashing beacons are generally mounted on each side of the sign panel and are actuated when the hazard exists. The major advantage of this type of display compared to changeable message signs is lower initial cost and the capability of agencies to fabricate this type of sign.

Transportation engineers have found it desirable to provide directional guidance to a particular road facility from other highways in the vicinity. This is accomplished by means of trailblazers erected at strategic locations, usually along major urban arterials, to indicate the direction to the nearest or most convenient point of access. The use of the word TO indicates that the road or street where the marker is posted is not a part of the indicated route, and that a driver is merely being directed progressively to the route.

9.3 DIAGRAMMATIC SIGNS

Diagrammatic signs are guide signs that depict a graphic view of the exit arrangement in relationship to the main highway. The use of such guide signs has been found to be superior to conventional guide signs for some interchangeable types.

Diagrammatic signs should be used at advance guide sign locations, for example, for splits having off-route movements to the left, optional lane splits, and exits with route discontinuity and left-exit-lane drops (see Figure 9.2). Diagrammatic signs, which may also be useful at 2-lane exits with an optional lane, should be designed in accordance with the MUTCD (*2*).

9.4 CHANGEABLE MESSAGE SIGNS (CMS)

Changeable message signs have been used in experimental and operational systems in several parts of the world during the last two decades (*3-11*). Changeable (variable) message signs (CMS) are real-time driver communication devices whereby the visual word, number, or symbolic display can be electronically or mechanically varied

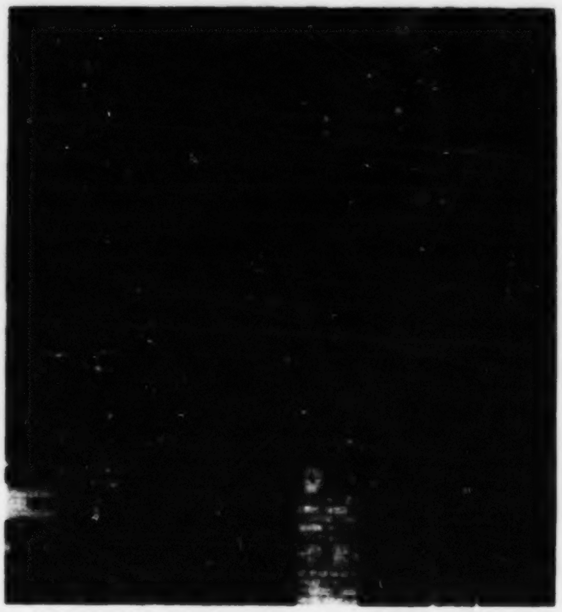


Figure 9.1. Static sign

as traffic conditions warrant. The MUTCD defines CMS as signs designed to have one or more messages that may be displayed or deleted as required (*2*). This type of sign has emerged as a valuable and important display tool for use by the traffic engineer to effectively communicate to the driver. While the conventional static sign conveys a message to the driver about a static situation, increasing hazard/incident occurrences require specific messages in the form of dynamic displays.

CMS displays can address a considerably wider range of traffic management functions. CMS signs are required when it is necessary to inform drivers of varying traffic, roadway, or environmental conditions. In addition to being effective when different types of driver actions are required, multiple-message displays can also be used to provide more specific information relative to locations, delay, etc. (*3*).

CMS systems can perform a critical role on high-speed highways by providing drivers with real-time information on a current roadway condition. However, to retain driver credibility a CMS system must supply timely, accurate, and reliable information. Once driver confidence is lost, even the most elaborate and costly system can quickly lose its effectiveness. Dudek has researched and conducted interviews with operations personnel to compile the following list of ways in which a driver's confidence can be lost (i.e., pitfalls to be avoided) (*10*):

- Displaying inaccurate or unreliable information
- Displaying information too late for drivers to make appropriate responses (untimely information)
- Displaying messages that drivers don't understand
- Displaying messages that are too long for drivers to read under prevailing highway speeds
- Not informing drivers of major incidents (adverse conditions) a large majority of the time
- Telling drivers something they already know
- Displaying information not related to environmental, roadway, or traffic conditions, or not related to routing
- Displaying garbled messages

CMS systems are becoming increasingly important in improving the safety and operation of existing highway and urban facilities. For example, CMS's will be representing the primary source of real-time motorist information in the Integrated Motorist Information System (IMIS) in the Northern Long Island Corridor (*12*). These signs, placed at key locations along the major roadways in the corridor, will indicate prevailing traffic and roadway conditions, and provide alternate routing information for the motorist where applicable. Applications of various types of driver information displays for corridor management are listed in Table 9.2.

CMS's can either be permanently installed or be transportable to serve a specific need. CMS systems range from fixed-time, onsite control to remote automatic control. Several computer-based freeway surveillance systems also utilize CMS's. Currently, however, these types of signs are most widely used to manage traffic through construction areas and maintenance zones and special events. Table 9.3 summarizes the techniques and possible traffic operations applications for CMS control.

A variety of CMS's are available to a highway agency, with each type having its own unique characteristics, while standards for CMS's have not been established and only minimum guidelines are provided in the MUTCD, a major research project, FHWA-RD-77-98 (*8*), summarizes CMS technology currently being utilized for traffic control applications and lists manufacturers for each display type.

The remaining portion of this section provides the traffic engineer with a working knowledge of the different types, features, uses, and effectiveness of CMS systems (*8,10,11*).

CMS Display Types

Of the three current types of CMS displays, the first requires a mechanical movement with appropriate electromechanical control to the sign's message. The second uses light sources arranged to form characters for varying the message. The third relies on an electrical impulse and mechanical movement to alter the display. (See Table 9.4 for a summary of these three different types of displays.)

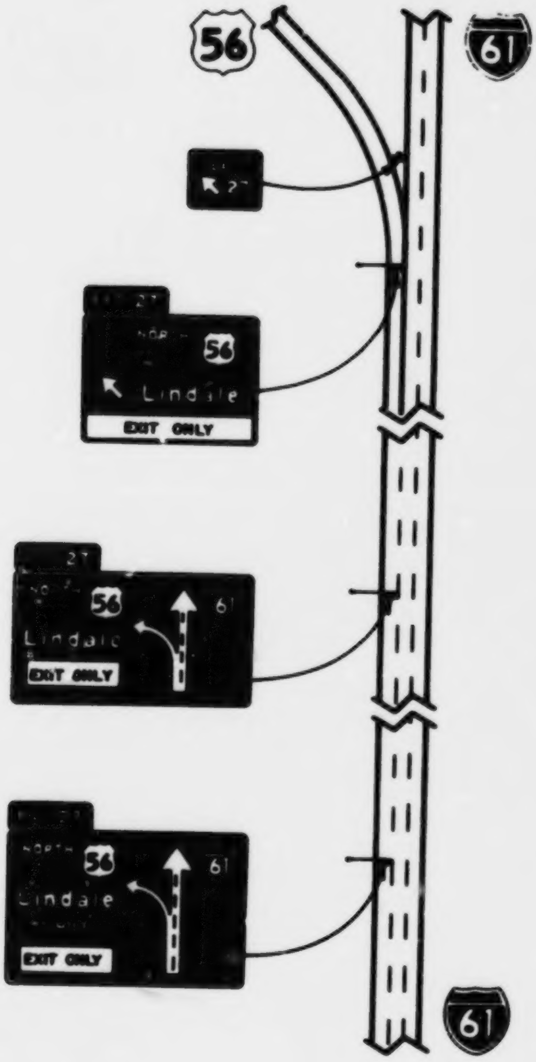


Figure 9.2. Diagrammatic sign for exit only on left-hand interchange land drop

Source: Reference (*2*)

Mechanical

Foldout Signs. The foldout sign is a relatively simple and effective 2-message sign, using a small motor to swing 2 hinged panels across the face of a standard sheet metal sign. This type of sign can display 2 separate messages or may display 1 message with the panels open (blank with the panels folded). The motor rotates these panels 180 deg to change the display.

Since foldout signs are relatively inexpensive, they have been widely used for a variety of information situations throughout the United States (i.e., school zone control, lane control, turn movements, high-water warning, and weigh stations). The major problems with these signs are

Table 9.2. Applications of changeable message and other types of real-time displays

Traffic management and diversion

- Freeway traffic advisory and incident management
- Freeway-to-freeway diversion
- Special events
- Adverse road and weather conditions
- Speed control

Warning of adverse conditions

- Adverse weather and environmental conditions (fog, smog, snow, rain, dust, wind, etc.)
- Adverse road conditions (ice, snow, slippery pavement, high water, etc.)
- High truck loads

Control at crossings

- Bridge control
- Tunnel control
- Mountain pass control
- Weigh station control
- Toll station control

Control during construction and maintenance

- Warnings
- Speed control
- Path control

Special-use lane and roadway control

- Reversible lanes
- Exclusive lanes
- Contraflow lanes
- Restricted roadways

Source: Reference (*10*)

309

a result of the highway environment and mechanical failures, such as the panels jamming due to severe ice or snow conditions. (See Figure 9.3 for an illustration of a foldout sign.)

Scroll Signs. The predominant face of the scroll sign containing several stored messages, is formed as a continuous belt of flexible material (plastic film), which is mounted on rollers at the sign's ends. The tape or film is then rotated until the desired message is properly positioned in the display window. The signs are designed with belts rotating either vertically or horizontally.

A desirable feature of this sign is that the enclosure is environmentally sealed and protected, plus some models have a standby power source and are manufactured for transportable operation. Two unfavorable characteristics are the limited number of maximum messages (typically 8 to 12) and the amount of time required to change messages which, if excessive, could cause driver confusion.

Rotating Drum Signs. Rotating drum signs generally contain 1 to 4 multifaced rotating drums, with each drum containing 2 to 6 message faces. Each face of a drum has one line of a fixed message formed to the panel. The drums are pivoted on the ends and rotated with a mechanical assembly to change the display. (For examples of this type of CMS installed in Dutch-John, Utah, and Duluth, Minnesota, see Figure 9.4.)

The drum sign's favorable characteristics include simple operation, good visibility, and the ability to operate from a 12-v power source or hand crank. Some unfavorable characteristics include the lack of environmental sealing, limit size on large characters, and on the number of faces on a drum, plus the necessity of replacing the entire fixed message panel to change a line of copy. In addition, mechanical failures can cause the drums to misregister when the limit switches are defective, which sometimes results in misleading information. Recently manufactured drum signs, however, have resolved the environmental problem by enclosing the face with a polycarbonate sheet.

Light Source

Neon Signs. The neon or inert gas sign uses neon tubing to form the legend characters. For variable-message applications, its use is limited to displaying 2 or more messages within the same sign space. Designs can be varied by stacking the neon tubing for each message or by separating each message on the sign face. For a large number of messages, however, the display has numerous layers of tubing which causes the light to reflect through the outermost tubes, thus making messages illegible or significantly enlarging the surface display area. Also, while experience with neon signs has shown that green neon is not acceptable for the highway environment, the New Jersey Turnpike Authority has had considerable success with red neon during all types of weather conditions. Currently, since neon signs have limited message variebility, most highway applications of this sign type are customized.

Fiber-Optic Signs. A fiber-optic display disperses light energy from a point light source through fiber bundles that form messages on the sign's face. Signs capable of displaying up to 14 messages have been developed in Europe. Although this type of display has been used predominantly for lane and pedestrian control, some fiber-optic displays have been developed for variable speed limits, weigh stations, inclement weather, and alternate routing applications.

Another example of fiber optics in traffic control is dual-color signal indications for left-turn lane control. Dallas, Texas, has over 100 intersections using fiber optics for this application. This allows a vertical stack of four 12-in. signal heads for overhead installations, with the bottom section providing both a green arrow and a yellow arrow during the change interval.

Lamp Matrix Signs. The display face of the lamp matrix display is formed by an array of incandescent lamps for each message line. Selectively illuminating the lamps in a character module permits the display of various characters. By utilizing a number of adjacent character modules, it is possible to construct various messages. Since each character module can display all letters of the alphabet and digits from 0 to 9, almost any message can be displayed if enough character modules are available. The number of messages available varies with system design. Early highway displays had only a limited number of hardwired messages. Newer display systems, however, which are used with computer equipment, provide considerable message flexibility.

Messages on lamp matrix displays can be shown statically or flashed on and off. Some systems can sequence message phrases and display messages in a run-on manner. The desired contrast of the sign display with ambient lighting is achieved by continuous variable photocell control of the power supply to the lamps. Messages will change almost instantaneously when a new message is selected.

This type of CMS has the advantages of a relatively simple operating principle, high target value, and message flexibility. It has also been environmentally tested with many operational systems. The lamp matrix sign does have several disadvantages in that the display requires continuous power to the sign, has high operating

Table 9.3. Sign control and operation techniques

CMS Sign Installation	Type of CMS Operation	Description	Possible Applications
Permanent	Remote automatic control	Sign messages are displayed and changed automatically by a remote control system when varying adverse environmental roadway or traffic conditions are sensed by detectors; manual-override capability is normally provided.	(a)
	Onsite automatic control	Sign messages are displayed and changed automatically by an onsite control system when varying adverse environmental roadway or traffic conditions are sensed by detectors.	(b)
	Remote manual control	Sign messages, based on varying environmental roadway or traffic conditions, are displayed and changed by sign operators from remote central office location.	(c)
	Onsite manual control	Sign messages, based on varying environmental roadway or traffic conditions, are displayed and changed by an operator using a control panel located at the sign site; in the case of a manually operated foldout sign, the sign is opened to display a message; and in both cases, personnel must travel to the sign site after the need for a message has been determined.	(d)
	Fixed-time automatic control	Sign messages are displayed and changed automatically at preselected times of the day.	(e)
	Fixed-time remote manual control	Sign messages are displayed and changed at preselected times by operators from a remote location.	(f)
	Fixed-time onsite manual control	Sign messages are displayed and changed at preselected times by operators at the sign site.	(f)
Transportable	Changeable message onsite control for unpredictable event	Sign is moved into place when an unpredictable event occurs (e.g., major accident); sign messages are displayed and changed onsite based on varying traffic conditions.	(g)
	Changeable message onsite control for predictable event	Sign is moved into place for a predictable event (e.g., special event, parade, holiday traffic congestion at a tunnel, bridge, etc.); sign messages are displayed and changed onsite, based on varying traffic conditions.	(h)
	Fixed message for unpredictable event	Signs is moved into place when an unpredictable event occurs; only one message is displayed.	(i)
	Fixed message for predictable event	Sign is moved into place for a predictable event; only one message is displayed.	(j)

[a] Traffic management and diversion (traffic advisory and incident management, freeway-to-freeway diversion, special events, adverse road and weather conditions, speed control); warning of adverse conditions (weather, environmental, road); control at crossings (bridge, tunnel, mountain pass); special roadway control (restricted roadways)

[b] Traffic advisory (warning of slow traffic, speed control); warning of adverse conditions (weather, environmental, road, high truck loads); control at crossings (bridge, tunnel, mountain pass); control during construction and maintenance; special roadway control (restricted roadways)

[c] Same as for remote automatic control; also, control at weigh stations and toll stations; control during construction and maintenance

[d] Same as for remote manual control; because of the delays in traveling to the CMS site(s), messages generally are not as timely in comparison with remote control operation

[e] Special-use lane and roadway control (reversible, exclusive, and contraflow lanes and restricted roadways)

[f] Same as for fixed-time automatic control

[g] Traffic management and diversion (traffic advisory and incident management, freeway-to-freeway diversion, adverse road and weather conditions)

[h] Traffic management and diversion (special events); control at crossings (bridge, tunnel, mountain pass); control during construction and maintenance

[i] Same as for changeable message onsite control for unpredictable event; displays and messages are not changed to respond to varying traffic conditions

[j] Same as for changeable message onsite control for predictable event; displays and messages are not changed to respond to varying traffic conditions

Source: Reference (*10*)

Table 9.4. Types of changeable-message sign displays

Category	Type
Mechanical	Foldout Scroll Rotating drum
Light source	Neon Fiber optics Lamp matrix
Electromechanical	Electromagnetic disc matrix Electromechanical flap matrix Electrostatic vane matrix

Source: Reference (5)

and maintenance costs, has many auxiliary control systems that require trained personnel, and experiences lamp failures which can make characters or messages confusing.

There are a relatively large number of lamp displays installed throughout the United States. Many of these are used for weigh station, variable speed limit, and lane control applications. The larger, more complex traffic management and information lamp projects include the following locations: Jones Falls Expressway — Baltimore, Maryland; Eisenhower Memorial Tunnel (I-70) — Colorado; I-75 — Cincinnati, Ohio; and Santa Monica Freeway (I-10) — Los Angeles, California. (See Figure 9.5 for an illustration.)

The Los Angeles Area Freeway Surveillance and Control System, in the early 1970s, installed 35 lamp CMS's on a 12-mi stretch of the Santa Monica Freeway between Los Angeles and Santa Monica. Currently, over half of these original signs have been relocated to other freeways at points of major decision, usually in advance of freeway-to-freeway ramps. The initial half-mile spacing of these signs was determined to be too close for effective motorist information. There are approximately 50 permanent CMS's in the greater Los Angeles area including both lamp and disc matrix signs.

Electromechanical

Electromagnetic Disc Matrix Signs. Disc matrix signs are similar to the lamp matrix with the exception that reflective discs rather than incandescent lamps are used to form the legend characters. This type of CMS has recently received widespread use in many highway CMS projects because of its projected lower operating and maintenance costs.

Most disc matrix signs utilize a 2-position, flip-disc technique. Usually the message lines consist of 20 variable-matrix modules, each with 35 individual flip discs that have a reflective yellow coating on one side and a flat black coating on the other side. Illumination of the sign face is provided by exterior lighting. A close-up of this module and the discs is shown in Figure 9.6.

Some new signs of this type utilize a 3-position, flip-disc technology to display messages with or without available sunlight. The reflective discs which are made of mylar plastic, have a small permanent magnet affixed to one side. Images and characters are formed on the display by rotating designated discs to the appropriate position. One side of the disc has a flat-black finish to blend with the background of the display face. If this side is revealed, the disc is not visible at normal viewing distances. The opposite side of the disc, however, is a bright fluorescent yellow. When this side of the disc is exposed to sunlight, it is highly visible and becomes an element of the character being formed. During nighttime and other low-light periods, the discs are rotated to a third, horizontal position. When in this horizontal position, the light from a common source located behind the disc modules passes through the display face to form the light points.

The disc matrix sign has the advantages of total message or display flexibility, low power consumption, and low

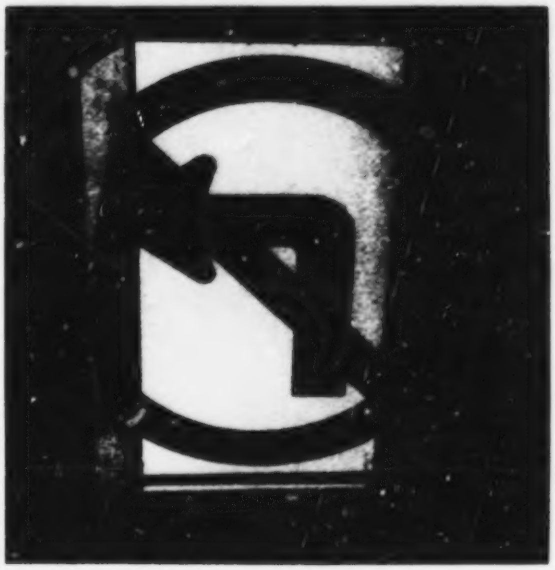


Figure 9.3. Foldout sign

Source: Reference (23)

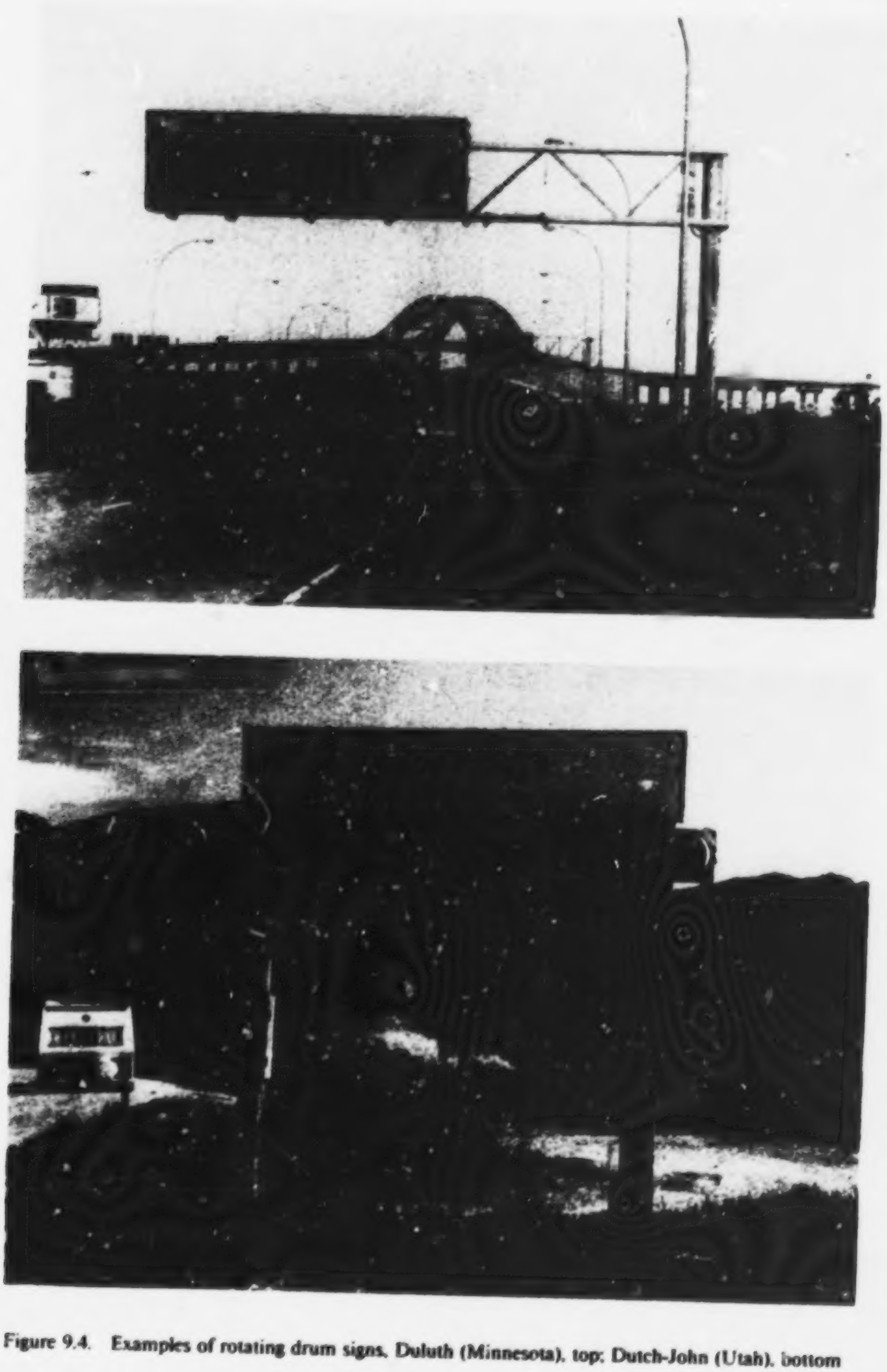


Figure 9.4. Examples of rotating drum signs, Duluth (Minnesota), top; Dutch-John (Utah), bottom

maintenance, while a sealed enclosure provides environmental protection. Favorable user comments cite the advantages of good message clarity under most light conditions, including no washout problem during intense sunlight. Disc signs, however, must be illuminated for nighttime use. This type of CMS also has reduced legibility distance, and loses visual impact on cloudy or overcast days. This method of message writing also could be considered a disadvantage compared with the lamp matrix's instantaneous message change capability. Since portions of the new and old messages are displayed concurrently while the new message is written, some confusion can occur. Even though messages cannot be flashed, some pictorial animation or simulated flashing is possible.

Several documented highway applications using disc signs include the following: Grand Rapids, Michigan; Tampa, Florida; Washington; Denver, Colorado; and Baltimore, Maryland. The Integrated Motorist Information System (IMIS) covering three major expressways in Long Island, New York, plans to install 74 signs of this type for advisory and diversionary information to motorists in order to minimize congestion and offer alternative routes. (For an example of a disc matrix sign, see Figure 9.7.)

Electromechanical Flap Matrix Signs. The message portion of the flap matrix sign is formed by an array of electromechanically actuated flaps, arranged on 5-in. by 7-in. matrix modules spaced a fixed distance apart. Typically, one side of each flap is black to match the sign background, with the other side usually white to display a white-on-black color combination. A reversible motor rotates the flaps 180 deg to form the legend characters. Exact shape presentation or display of lower case lettering types is not possible.

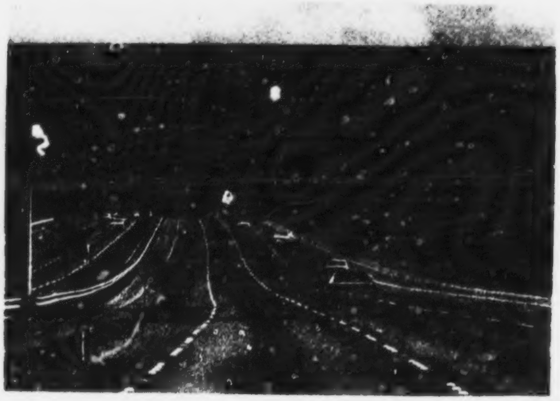


Figure 9.5. Lamp matrix sign

Source: Reference (*25*)

Messages are changed by inscribing the new message from left to right on each line in sequence. During a message change, parts of the new and old messages are visible since at least 2 sec are required to change one line of average length on a sign. Up to 10 sec are required to change the entire message.

Since surveys (*8*) have been reported on only one known highway installation on King Avenue Overpass in Baltimore, Maryland, it appears that only limited experience has been gained in using the electromechanical flap matrix sign.

Tri-Color Signs. The viewing face is formed by a matrix of 2½-in. square rotating 3-sided elements. The elements reveal one of 3 colors (e.g., white, black, and fluorescent yellow); thus, several color combinations of letters and backgrounds can be displayed. The element itself is electromagnetic. Surrounding the armature contained in the element is a cylindrical 3-pole permanent magnet which rotates to orient to an armature coil. When energized, it is magnetically detented after the power is removed. A typical freeway overhead sign may contain 2,430 elements. See Figure 9.8 for an example of a Tri-Color sign element.

Currently, this type of sign is the only CMS manufactured that can display both regulatory and warning messages with the proper color combination. Messages on this sign are normally statically displayed. Font size can be changed to range from 4-in. to 6-in. wide and 5-in. to 9-in. high. External lighting is required for night visibility.

9.5 TRANSPORTABLE SIGNS

In some situations, when permanent CMS's are not available on the highway to be controlled, it may be desirable to use transportable signs to display real-time information. Transportable capabilities allow the highway agency to move the CMS into place prior to predictable events (e.g., special events), or to manage traffic when unpredictable major incidents occur. It should be

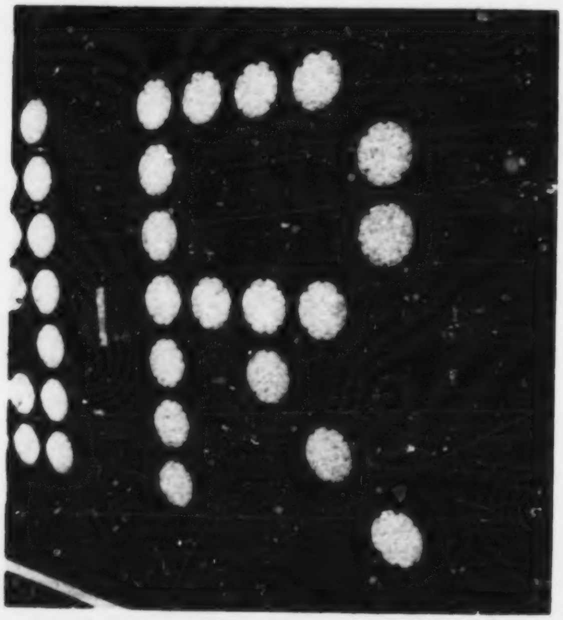


Figure 9.6. Closeup of 2-position disc matrix sign module

Figure 9.7. Disc matrix sign, I-70 West, Denver (Colorado)

recognized that, in the latter case, the delay in displaying a message following an accident may at times be considerable because of the travel time to the site needed by service personnel.

Transportable signs include the following three types:

- Truck- or trailer-mounted signs
- Pickup signs (leg-supported signs that can be placed in a truck or trailer, hauled to a site, and set out on the roadside)
- Ground-mounted, with removable, transportable message panels

Examples of the truck-mounted signs used in response to major incidents are the Caltrans major incident response units shown in Figure 9.9. The message inserts are signs mounted on a rigid-frame support. A library of message inserts is stored on each truck, and messages are displayed in various combinations as directed by the situation. Lamp-matrix CMS's mounted on the back of pickup trucks are also used by the response team to manage traffic during incident or special events conditions. This sign has the same capabilities as a permanent lamp sign and can be moved to any location. This type of truck or trailer-mounted sign may have limitations with respect to response time, size, and power requirements; it is best suited to predictable events. The Caltrans response team is on call at all times, thus reducing response time to a minimum. Transportable CMS's have proven superior to fixed CMS locations for end of queue management because of mobility (*18*).

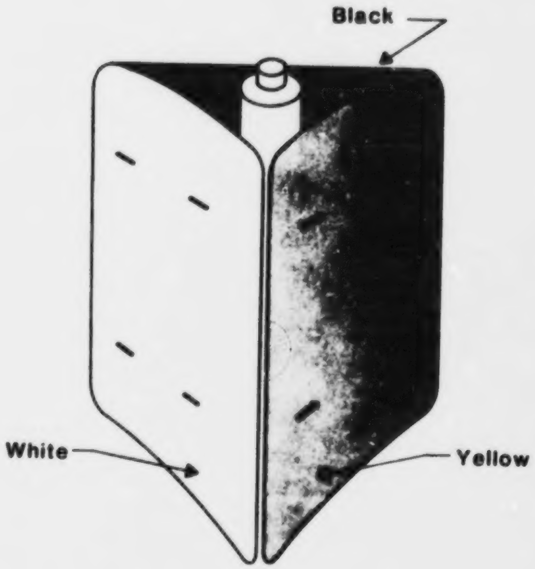


Figure 9.8. Tri-Color sign element

Source: Reference (*23*)

9.6 HIGHWAY ADVISORY RADIO (HAR)

The Highway Advisory Radio (HAR) is a means of providing highway and traffic-related messages to the driver using his existing AM radio receiver. Typically, the service is provided at either end (i.e., 530 and 1610 kHz) of the AM band. HAR locations are restricted because either commercial stations broadcasting on frequencies too close to HAR's, or the Travelers Information Station broadcasters (National Park Service, Forest Service, Airports, Coast Guard, etc.) who use the same HAR frequencies are nearby. Use of these frequencies can be authorized by the Federal Communication Commission (FCC) on a developmental license or under FCC Rules and Regulations, Part 15, without a license which permits low power communication devices. At best, however, Part 15 systems provide marginal coverage and are not likely to prove satisfactory for most traffic control and advisory applications (*19*).

A HAR broadcast system consists of a low-powered AM transmitter which is matched to either an induction cable antenna or vertical monopole antenna (see Figure 9.10) and is modulated with a solid state voice storage unit. Typically, the AM transmitter is connected to the voice storage unit via leased telephone lines. Generally, the monopole antenna has been used in most existing installations. The cable antenna has been rarely used because of the high cost of installation.

Vertical Antenna HAR Systems

A single whip antenna may be used or several antennas can be spaced along the highway and electronically interconnected. Each antenna radiates a signal in all directions, thus forming a circular transmission zone. Some of the primary advantages and disadvantages of the whip antenna are as follows (*7*):

- It is physically small and can be installed in a relatively small space.
- It is relatively easy to install. It can be installed in a short time in various environments over earth or pavement, on a building tower, etc.

316

- It can be easily relocated.
- It will usually be visible, but can be partially camouflaged.
- It can be placed several hundred feet from the highway.
- It is subject to damage by weather, accident, or vandalism.
- It requires a matching network (or series inductance) that is efficient, stable, reliable, and easily tunable.
- It provides a circular zone of coverage that may interfere with other coverage zones on adjacent highways.
- It will usually be less costly to purchase and install than a cable antenna.

Induction Cable Antenna HAR Systems

The second method of broadcast utilizes a roadside cable instead of conventional vertical antennas. The radio signals are "narrow cast" by directional induction radio transmission and can thus be confined to the width of a multilaned highway.

One of the characteristics of the cable antenna is that a strong, but highly localized induction-type radio signal can be produced within a short lateral distance of 100 to 150 ft from the cable. This is sufficient to produce a good signal for the width of a multilane highway while restricting the field. At a distance of several hundred ft from the cable, the field is below the effective response value of typical automobile receivers. This results in a relatively high degree of efficiency in the use of the radio spectrum for roadway communications, as the same carrier frequency may be utilized without interference on several highways in one area. Another feature is that the system can be designed such that different messages can be broadcast over two separate frequencies on the same cable. Thus, messages could be individualized by direction of travel.

Several advantages and disadvantages relative to the use of cable antennas are as follows:

- It must physically extend the full length of the coverage zone.
- It can provide continuous coverage through tunnels, in buildings, under overpasses, etc.
- It may be placed above or below ground.
- If installed below ground, it is not subject to damage by weather or vandalism.
- If buried, it is more costly to purchase, install, and relocate; however, it can be made virtually invisible.
- It is not easily installed in some areas already built up with concrete pavement and highway structures, such as through a highway interchange or intersection.
- The cable antenna is easily connected electrically and requires no matching network or tuning adjustment.
- The radiation zone is confined to within 100 ft or less from the cable, and thus minimizes interference with nearby coverage zones.
- It must be placed close to the highway.
- The radiation is stable with temperature and weather and is relatively unaffected by the type of soil if buried.

HAR Experience

Certain shortcomings exist with the present HAR system. In developing a system which utilizes AM receivers, various compromises have had to be accepted. For example, the motorist is required to tune to the HAR broadcast manually, and the reception zone of the broadcast is directly related to the out-of-band tuning of the receiver. In addition, the broadcast is not received by all AM receivers. However, the benefits outweigh some of these problems since HAR can be used effectively to provide real-time traffic information relative to traffic congestion, construction, and maintenance operations, as well as information on specific highway environmental conditions.

Outlined below are some of the experiences obtained from HAR users as presented by Mammano in a report by the California Institute of Transportation Studies (*11*):

- Over 75 percent of the commercially available AM automotive radios will tune to 530 kHz; only 50 percent will tune to 1610 kHz.
- Many local authorities do not provide adequate documentation in applying to the FCC for Travelers Information System (TIS) authorizations. Hence, some licenses are granted in 2 months while others take over 6 months.
- One of the accepted types of transmitters requires an in-line amplifier to fully modulate the AM carrier from the leased telephone line.
- Most vertical monopole antennas require an RF impedance bridge for optimal tuning.
- One of the advance visual signs for an HAR system should indicate if the system is in operation (ON/OFF).

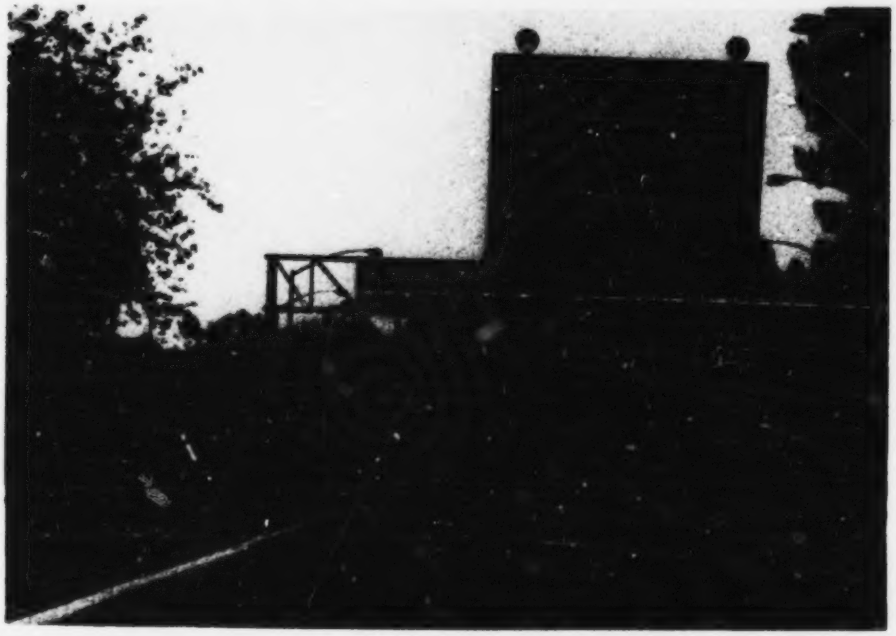
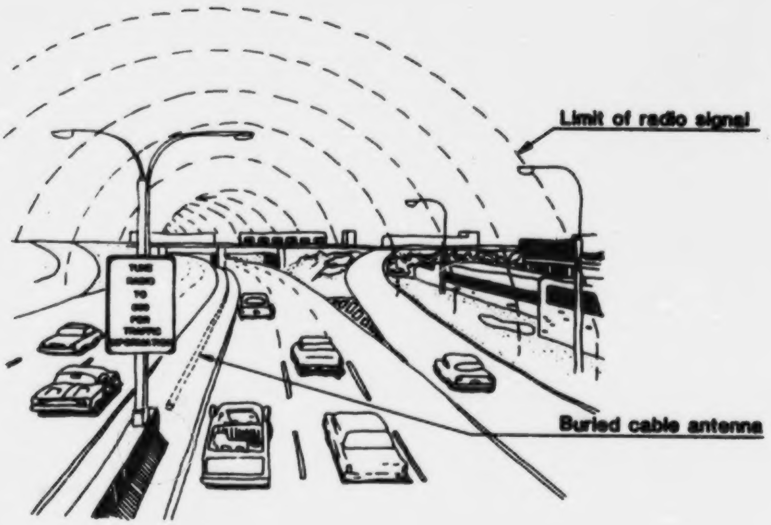
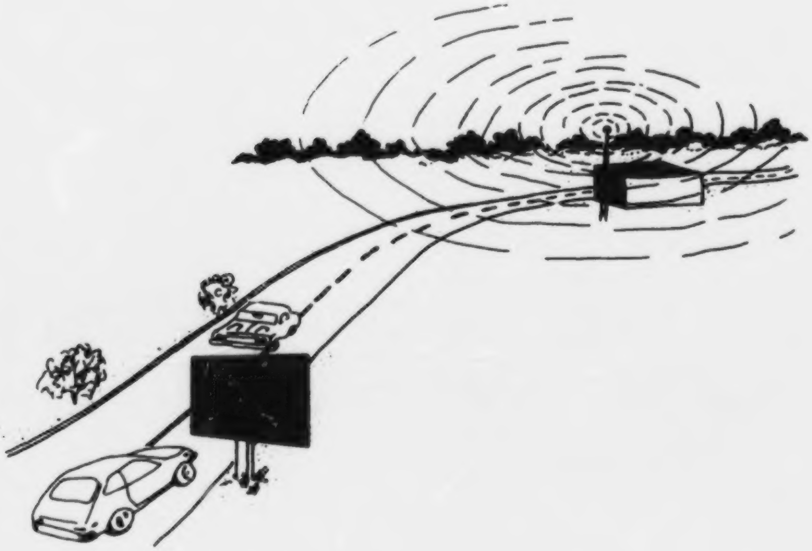


Figure 9.9. Examples of transportable CMS's used for major incident response


Limit of radio signal
Buried cable antenna

(A) Cable antenna system



(B) Vertical monopole antenna system

Figure 9.10. Typical highway advisory radio (HAR) antennas

Source: Reference (*11*)

- HAR systems should use either two pairs of leased lines (one to modulate the transmitter and the other to monitor the broadcast), or a sensitive receiver to monitor the roadway's broadcast.
- Sufficient roadway surveillance is required to assure that timely and credible information is being broadcast.

Examples of Existing Systems. Operational or experimental audio systems have been installed at the following locations:

- Los Angeles International Airport
- Houston Intercontinental Airport
- Colorado (Colorado Division of Highways, District 1)
- Philadelphia (Delaware Valley Regional Planning Commission)
- Minneapolis (Minnesota Department of Highways)
- Beaumont (Texas Department of Highways and Public Transportation)
- Wyoming (Wyoming State Highway Department)
- Washington (Washington Department of Transportation)
- Chicago (Illinois Department of Transportation — 5 systems)
- Yellowstone National Park
- Disneyworld

The remainder of this section describes some of the above systems to illustrate the practice in some states. A list of HAR users as of 1980 can be found in Reference (*20*).

A good example of a low-power radio broadcasting system utilized to provide driver information is that owned by the Los Angeles Airport Authority. This system consists of a buried-cable AM radio system with broadcasts transmitted via 530 kHz. Signs on I-405 in advance of airport exits advise motorists to tune to the station for airport information. The objective of the system is to minimize the number of circuitous trips around the terminal loop, a situation which creates severe traffic congestion. Basic messages guide motorists to terminal parking and to specific terminals. Over a mile is buried under Century Avenue, another mile is buried along Sepulveda Boulevard, and over 2 mi are buried along I-405 on the approaches to the terminal loop road. Prerecorded tapes are selected and played depending upon roadway and parking conditions. Information to the central control room is supplied by a closed circuit television camera and parking lot attendants. The messages range in length from 20 to 120 sec.

Another functional system is employed at the Houston Intercontinental Airport to provide information concerning parking conditions. The system output is low-power and uses tape cartridge broadcasts. Depending upon various parking conditions, designated tapes are initiated. Transmission is made using single-dipole, circular radiation antennas. Two antennas are used in the system to provide a broadcast zone of approximately 6.0 mi with the present configuration. The transmitter and antennas are connected in circuit using existing phone line. With the low-power output, broadcasts may be conducted on any frequency between 530 and 1610 kHz. However, broadcasts are made on 1100 kHz without interference from local commercial broadcasts.

In Colorado, motorists approaching the Eisenhower Tunnel on I-70 may tune their radios to 1610 kHz and receive advisory information concerning tunnel conditions, road surface conditions (approaching the tunnel and at Loveland and Berthoud Pass), traffic conditions and alternate routing if necessary. The information is gathered at the tunnel control center and appropriate messages are taped and played back over telephone lines to transmitters located at Dumont on the east and Dillon on the west side. These HAR systems operate with an FCC experimental radio license. Both transmitters broadcast on 1610 kHz with up to 10 watts of RF power into above ground monopole antennas.

In 1975, the Delaware Valley Regional Planning Commission (DVRPC) started operating a HAR system on the Walt Whitman Bridge in Philadelphia. The system informs inbound motorists from 6:30 a.m. to 9:00 a.m. of free parking to encourage the use of mass transit, reduced toll rates for carpools, and traffic conditions on the Schuykill Expressway (I-676), the main arterial to the CBD. This HAR system contains 6,000 ft of cable antenna that was suspended on the bridge, a 10-w AM transmitter, and a telephone-line interconnected tape deck. It operates on 530 kHz with an FCC experimental radio station license. Five additional HAR systems were installed in July, 1976. Each operates at 530 kHz within FCC Rules and Regulations, Part 15. Each system contains a low-power AM Transmitter and 9,000 ft of buried cable antenna.

The Minnesota Department of Highways installed a HAR system on I-35W in Minneapolis as part of an extensive surveillance and control system. The system contains 1 mi of cable antenna, a 10-watt AM transmitter, and a tape deck with a telephone interconnect. The transmitter operates at 530 kHz with an FCC experimental radio station license.

From the experience gained from existing HAR installations the FHWA has developed guidelines for the use of this system (i.e., User's Guide, Design Guidelines, and Executive Summary). Also a *Highway Advisory Radio Message Development Guide* has been recently developed to help station operators prepare HAR messages.

Automatic Highway Advisory Radio (AHAR)

A prototype of an Automatic Highway Advisory Radio (AHAR) has been developed for testing and evaluation. The AHAR system uses roadside transmitters and in-vehicle receivers to provide motorists automatically with noncommercial information pertaining to traffic, road and weather conditions, travel advisories, and general tourist information. The motorist can preselect the class of information to be received (i.e., traffic advisory or trip information). The AHAR system also has an overriding emergency information feature. This new technique should improve the motorists' attention to the driving process and, thus, improve safety by relieving them from having to search for the message they need. In addition, not having to listen to a number of irrelevant messages should assist in message retention.

The concept of AHAR is illustrated in Figure 9.11 (*21*). Figure 9.11(a) shows the basic components that make up the system. Figure 9.11(b) shows the arrangement of the system along a highway. A vehicle moving from right to left first enters the enable receive zone. This transmitter continuously transmits an enable code consisting of a single dual-tone multiple-frequency (CTMF) digit. The scan zone represents a time allowance for a scanning receiver to locate the frequency. The width of the enable receiver zone need only be sufficient for the receiver, after locking on, to receive the enabling code. Once enabled, the vehicular receive stops scanning and waits for the message. The message is received after the vehicle enters the message receive zone. Width of the message receive zone should be about 3 mi for the real-time analog approach. This will permit a vehicle moving at 60 mph to receive an uninterrupted 60-sec message at least twice from beginning to end.

A pilot demonstration of a AHAR system has been completed in Tampa/St. Petersburg, Florida. The AHAR transmitter provided messages of traffic conditions on the Howard Frankland Bridge, giving the participating motorist the alternative of using a diversion route when traffic conditions warranted. Conclusions from the demonstration project include the following (*21*):

- The AHAR concept has merit. Timely traffic information provided at locations where motorists are able to make a choice of alternate routes can influence their decision-making process. Participants indicated that about 42 percent of the messages received influenced their choices of routes.
- Unless the cost of a mass produced in-vehicle receiver can be reduced to $100 or less (1983 prices), or incorporated into a standard automobile broadcast receiver at a reasonable cost, widespread acceptance by motorists is not likely.

9.7 MOTORIST AID SYSTEMS

Motorist aid systems can be classified as follows:

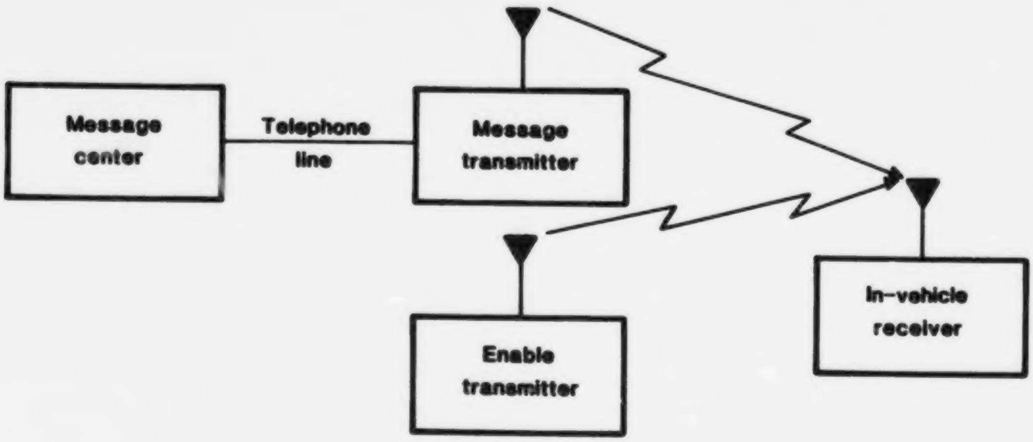
- Call box and emergency telephones
  - Coded pushbutton call-box
  - Two-way voice
  - Commercial telephone
- In-vehicle communications
  - CB radio
  - Commercial automobile telephone
- Patrols
  - Police/highway
  - Courtesy (private or public)

Call Box and Emergency Telephone Systems

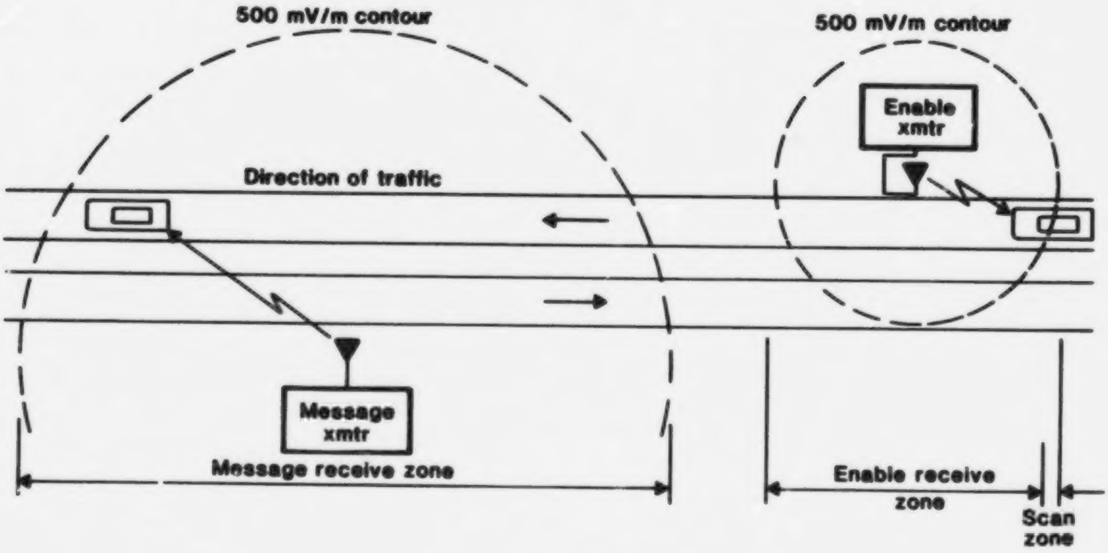
One of the earliest incident-detection systems used motorist call boxes or emergency telephones. The approximately 50 emergency telephone systems which have been installed in the United States to provide the motorist with a means of summoning aid have been shown to be valuable. Motorists experiencing, or witnessing, an incident have used the nearest call box or telephone to inform the operating agency of the nature of the incident. Telephones are generally preferred because voice communication gives the motorist an opportunity to explain exactly what services are required. However, the call box with coded message buttons is less costly (20 to 25 percent) than a telephone requiring voice transmission.

The major advantage of a motorist call system is that it is an efficient system for signaling a motorist's need for service. A major disadvantage is the delay associated with the motorist determining that an incident has occurred, recognizing that the proper action involves using the call box, locating the nearest call box, and then proceeding safely to the call box to inform the operating agency. Two disadvantages are that delay can be quite significant, and, also, that these systems are susceptible to vandalism and false alarms.

Mammano (*17*) conducted a survey of call boxes and emergency telephones in 1982, and identified 34 operating systems of this type. The 34 operating systems were found in 20 states and represented a reduction of 15 systems since 1976. The principal reasons for reduction are vandalism and high operating and maintenance costs. Five states — Florida, Rhode Island, Michigan,


Message center
Telephone line
Message transmitter
Enable transmitter
In-vehicle receiver

(A) AHAR system components


500 mV/m contour
500 mV/m contour
Direction of traffic
Enable xmtr
Message xmtr
Message receive zone
Enable receive zone
Scan zone

(B) Transmitter placement

Figure 9.11. Automatic highway advisory radio (AHAR)

Source: Reference (*11*)

Connecticut, and Louisiana — have installed systems in the last 6 years.

However, some freeway operating agencies indicate that this type of motorist aid system is the best public relations device in the system. An example is in Detroit, Michigan, where the Surveillance Control and Driver Information (SCANDI) has been installed. (For some illustrations of emergency call boxes and telephones, see Figures 4.25 and 4.26.)

9.8 CITIZEN BAND (CB) RADIO

The need for a positive response that is less expensive and safer than the telephone system has led the FHWA to research in-vehicular, 2-way motorist-aid systems. These systems would allow motorists to remain in their vehicles and use their citizen band (CB) radios to render aid.

Requests for assistance are broadcast over Channel 9, which was designated as an official emergency channel by the FCC in 1970. Since then, several national volunteer citizen groups (i.e., REACT and ALERT) have been organized to provide motorist assistance by monitoring at mobile and fixed stations that interface with public safety agencies dispatching the service required. Depending on the geographic characteristics of the area, calls transmitted on this band may be effective for distances up to 20 mi (*11*).

The National Highway Traffic Safety Administration sponsors the National Emergency Aid Radio (NEAR) to develop CB system improvements and promote the use of CB radio in emergency situations. This national organization has over 30 states actively participating in the NEAR program. The evaluation of this program clearly indicates the value of a 2-way, in-vehicular radio and the need for a fully organized, well-structured communication system for this method of motorist aid to be successful. State and private organizations are attempting to provide the systems, while the NEAR program provides the structure required.

Some state agencies and private groups are actively pursuing CB motorist-aid programs by the following methods:

- Organizing volunteer groups to monitor more stations to provide an intense local area coverage
- Using the CB as an input for a wide-area motorist information system
- Involving state law enforcement agencies
- Extending the effective transmission range of CB through equipment enhancement (i.e., BEAR and CB/Aids systems)

(See Table 9.5 for a summary of the characteristics of CB motorist-aid applications.)

Broad Emergency Assistance Radio (BEAR) System

The Michigan Broad Emergency Assistance Radio (BEAR) system, developed by the state, uses the CB radio to assist motorists. The system consists of 10 remote (relay) stations along a 139-mi section of I-96 between Detroit and Grand Rapids, Michigan. (See Figure 4.27) The unattended remote stations are linked by dedicated leased telephone lines to the Michigan State Police in East Lansing.

Following a shutdown of the system in 1982 because of a lack of operating funds, the state police initiated a program to have volunteers operate the system from the state police barracks in East Lansing. Volunteers are made up of senior citizens, criminology students from the University of Michigan, welfare personnel, and other volunteers.

The BEAR system requires that the dispatcher (volunteer) monitor a display board to which all 10 remote stations are connected. The remote stations have a tone-squelching technique, allowing the motorist with the strongest signal to access the system. Once the motorist has made contact with the police monitor, the monitor advises the motorist to stand by while the monitor turns to Channel 19 to listen and then call to verify that a motorist needs assistance. Upon confirming the distress call, the monitor returns to Channel 9 and talks with the distressed motorist or acknowledges the contribution of the good samaritan caller — the motorist who reported a vehicle needing assistance. Once verified, assistance instructions are then sent from the dispatcher to 1 in 5 individual state police posts by means of police radio, telephone, or teletype.

The system operates 24 hr/day, 7 days/week. All calls received over the system have to be monitored, which places a burden on the operating staff for this coverage. At present, volunteer groups handle approximately 30 percent of the calls on the system. This cooperation with the State Police has worked quite well. Based on an expected 10-yr system life, the cost per call is currently $27.37 (*15*).

Citizen Band Automatic Interconnect Digital System (CB/Aids)

The FHWA has initiated a study to determine the technical feasibility of an automatic telephone interconnect device which could be used with a CB radio link for motorist emergencies and assistance. A pilot program has been established in DeKalb County, Georgia, approximately 10 mi northeast of Atlanta.

The basic concept of this system (see Figure 9.12) is that motorists can establish communications from their vehicles to a monitoring system through an automatic radio-to-telephone connection. To make a connection, the motorist would use a digital adapter attached to the CB radio (see Figure 9.13). Two pushbuttons on the digital adapter make it possible to select either an "emergency" (E) or "assistance" (A) monitor. By pressing the appropriate button and then keying the microphone, the motorist transmits a short burst of data, including the motorist's identification number and the E or A call identification. The decoding circuitry on a CB-base-station transceiver, at an unattended remote station, receives and stores the data. After verifying the data, the circuitry then automatically dials either the emergency monitoring telephone number or the assistance-monitoring telephone number. The audible telephone touch tone codes are then transmitted to let the motorist know that the call is being placed. The remote station monitor communicates directly with the motorist using standard radio procedure. After determining the response required and ensuring that the request is processed, the monitor terminates the call. The system automatically resets to receive the next call. One feature to reduce emergency-response time allows volunteer groups to answer assistance calls, thus freeing the police to respond only to emergency calls.

An example of an automatic CB system is the Chicago Area Surveillance Project (CASP). In the CASP system, CB radios are used as an adjunct to their automatic incident detection capability. When an incident alarm is generated by the automatic system, the nearest roadside CB unit is selected and monitored by the system operation to determine the extent of the incident. There are 5 CB units on the Eisenhower Expressway. The System covers approximately 15 mi. The CB units are spaced approximately 3 mi apart. Although there are no formal evaluation data available, system personnel indicate a very positive attitude on the usefulness of CB monitoring.Plans to expand the coverage for approximately 100 mi of the freeway system are under way.

New York is planning to install a CB system similar to the one in Chicago. This CB system will be a part of the

Table 9.5. Characteristics of various citizenband (CB) radio motorist aid applications

CB Motorist Aid Applications	Communications		Coverage		Response Time	False Alarm Rate	Communication Coordination	Motorist Confidence	Special Features
	1-way	2-way	Time (Hr)	Area					
Volunteer monitoring		X	24	Limited	Fair	Average	Limited	Fair	Good samaritan, mobile, and/or base operation
Control center operations[b]	X	X	24	Broad	Good	Low	Excellent	Good	Radio station broadcasting, CCTV, speed-call telephone, UHF-FM
Police monitoring		X	24	Broad	Excellent	Low	Excellent	Excellent	Security, assurance, good samaritan
BEAR	X	X[c]	24	Broad	Good	Low	Excellent	Good	Extended geographical coverage, good samaritan
CB/Aid System	X	X	24	Broad	Excellent	Very Low	Excellent	Excellent	Automatic identification, extended geographical coverage, digital signaling, priority messaging, good samaritan

[a] Ratings are relative to each other.
[b] These could include listening post systems.
[c] The distressed motorist may not have 2-way communication if a good samaritan places the call.

Source: Reference (*14*)

IMIS for the Long Island Expressway and Grand Central/Northern State Parkway, totaling 75 mi with about 25 roadside CB station units, spaced at 3-mi intervals. Communications requirements are 2 wire pairs for each unit. One pair for addressing the roadside units and the other for returning the voice transmission. A remote power turn-on capability can be incorporated without any additional pairs. On-duty IMIS operators will also be assigned to monitor the CB system.

9.9 COMMERCIAL RADIOS

Commercial radio has significant potential for becoming an important element of a driver information system. It has wide-area coverage and the opportunity of reaching a large segment of the motoring public. Major disadvantages of commercial radio include delayed and inaccurate messages to the motorists. Dudek and Carvell (*16*) have indicated the following 6 typical sources of information on traffic conditions that are utilized by commercial radio stations:

- Police hot-line — News information service is made available to radio stations by police departments.
- Police radio — Many stations monitor police radio frequencies to obtain news information.
- Mobile news vehicle — Radio stations may have mobile news vehicles with two-way radios.
- Traffic spotters — Broadcasters are located on top of a tall building from which several major routes can be observed.
- Aerial observer — Airborne observer also has broadcast ability.
- Police officer in studio — Off-duty police officer in the station utilizes his experience and police information service.

All of the previously mentioned techniques for obtaining traffic information could be improved. It is obvious that if commercial radio is to be an effective driver information tool, then considerable cooperation between commercial stations and operating agencies is necessary.

Two successful generations utilizing several of the above information sources are the Michigan Emergency Patrol (MEP) in Detroit, Michigan, and the SHADOW Network, Inc., in Chicago, New York, and Philadelphia. The SHADOW Network, Inc., a private organization, uses airplanes, helicopters, radio-equipped mobile units, high-powered telescopes, and "SHADOW boxes" (CB receivers at listening posts) to report traffic conditions. The information goes directly to a SHADOW studio. Direct voice reports from the drivers and pilots are available to subscriber radio stations. This information can be provided on a teleprinter, and then be broadcast at regular intervals on various radio stations, or be broadcast live in an emergency. The reports are transmitted at times specified by the subscriber stations and, according to the contract, information must be aired within 4 min.

The MEP is a volunteer organization that operates a base station from a building in central Detroit and communicates with CB mobiles throughout most of the Detroit metropolitan area. Support is provided by several local broadcast stations. In return, the MEP provides traffic bulletins to the commercial radio stations.

Another method for providing information to motorists is rebroadcasting to override the AM band in tunnels when traffic advisory information is required. Systems of this type operate in various tunnels in Fort Lauderdale, Florida, and Maryland (Harbor Tunnel). A prototype system which has been operating in New York (Holland Tunnel) is being enhanced with this override capability.

9.10 CELLULAR MOBILE PHONE SYSTEM

This is another system with potential use for driver information. If a transportation management center is available, then the public can be given a phone number to call if they desire information or to report on traffic conditions. With this approach, the mobile phone serves as a pretrip or alternate route planning device.

Many companies and organizations have developed and are now implementing this high-capacity mobile phone system. The system utilizes a dialed connection between mobile units and the national telephone network to provide a full-service telephone within the vehicle. The service areas are divided into an array of small cells with a radius from one to several miles. Each cell serves a limited number of users on the assigned frequency. By using low-power equipment, the small cell design allows the radio frequency used within one cell to be reused in other cells within the same city, provided the calls are far enough apart to avoid interfering with each other. As the number of users and calls increase, the cells are split into smaller cells to increase system capacity. The system operates in the 800 MHz spectrum, and typical mobile transmitter power is 12 watts.

A key feature is the switching and control function which is performed via a mobile switching office. Through the national telephone network electronic switching systems, the mobile switching offices process and coordinate calls almost instantly, automatically switching individual calls from one cell to the next as the caller drives across service areas.

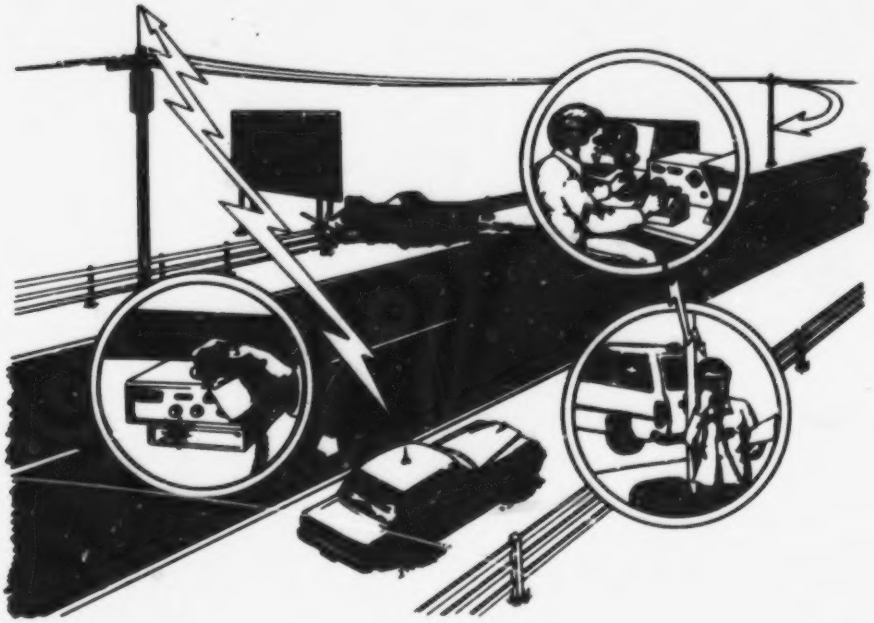


Figure 9.12. CB/Aids basic concept

Source: Reference (*17*)

9.11 DESIGN GUIDE

The U.S. Department of Transportation, FHWA, has conducted a major research project, ***Human Factors Requirements for Real-Time Motorist Information Displays*** (*3*), to provide the traffic engineer with practical guidelines for the development, design and operation of driver information needs, both visual and auditory, for freeway traffic management.

Figure 9.13. CB digital adapter

Source: Reference (*11*)

This project emphasizes several points, including (1) the recommended message composition which is to be displayed in various traffic situations, (2) the manner in which such messages are to be displayed (such as formatting, coding, style, length, load, redundancy, and number of repetitions), and (3) where CMS's should be placed to be most effective with respect to different situations.

This design guide has recently been condensed to a ***Manual on Real-Time Motorist Information Displays*** (*22*).

9.12 TRANSPORTATION MANAGEMENT CENTER

A centrally organized operation can provide excellent coordination and communication with the law enforcement agencies, emergency services, and broadcast media. Thus, a transportation management center is a key requirement for a successful driver information system. In order to be able to transmit timely, accurate, and useful

326

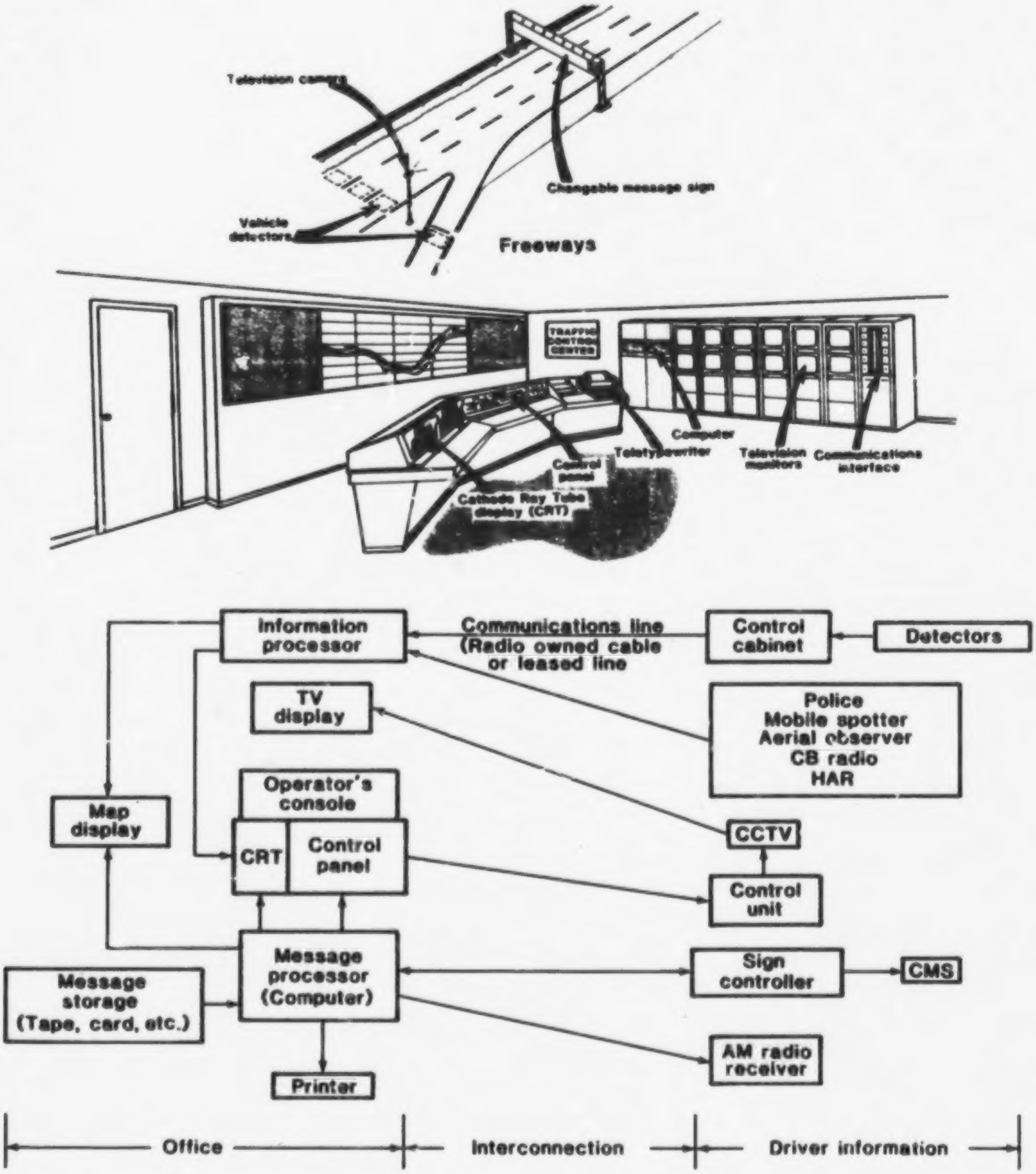

Television camera
Changable message sign
Vehicle detectors
Freeways
TRAFFIC CONTROL CENTER
Computer
Teletypewriter
Television monitors
Communications interface
Control panel
Cathode Ray Tube display (CRT)
Information processor
Communications line (Radio owned cable or leased line
Control cabinet
Detectors
TV display
Police
Mobile spotter
Aerial observer
CB radio
HAR
Operator's console
Map display
CRT
Control panel
CCTV
Control unit
Message processor (Computer)
Message storage (Tape, card, etc.)
Sign controller
CMS
AM radio receiver
Printer
Office
Interconnection
Driver information

Figure 9.14. Relationship of the components of a driver information system

Source: Reference (27)

information to drivers, it is necessary to have a system for collecting, analyzing, and displaying information on traffic flow conditions.

Freeway traffic advisory and incident management CMS systems with permanently mounted signs and transportable truck- or trailer-mounted signs are computer-based systems integrated with electronic surveillance. Central computers serve several functions, including processing data from field sensors, displaying traffic characteristic information to operators, storing CMS messages, scanning the status of the CMS's and other system hardware, and in some installations, automatically changing messages on the CMS's. (For the typical components of a driver information system, see Figure 9.14.)

Agencies designing new second-generation CMS systems are now considering the feasibility of placing microcomputers at each sign site in order to have more intelligence in the field. This approach may save considerable transmission costs, particularly when the system extends for several miles.

9.13 LANE-USE CONTROL SIGNALS

According to the MUTCD (*2*), "Lane-use control signals are special overhead signals having indications used to permit or prohibit the use of specific lanes of a street or highway or to indicate the impending prohibitions of use." Installations are distinguished by the placement of these special signals over a certain lane or lanes of the roadway and by their distinctive shapes and symbols. Supplementary signs are often used to explain their meaning and intent.

Lane-use control signals are most commonly used for reversible-lane control. They may also be used to accomplish the following:

- Clear a freeway lane(s) at any time this is deemed necessary
- Indicate the termination of a freeway lane
- Indicate blockage of a lane ahead by an accident or a hazard
- Permanently operate a 2-way street with an unequal lane distribution
- Operate a 2-way street in a 1-way mode during peak periods

Such signals consist of a red X on an opaque background or a green arrow on an opaque background, with the arrowhead pointing downward. In addition to these two symbols, a yellow X may be used. Only a single indication is displayed at a time for each lane in either direction.

An example of lane-use control signals for reversible-lane control is shown in Figure 9.15. Lane-use control signals are not mandatory for reversible lanes or for their other purposes. Signing has often been used for these purposes. However, properly designed and operated lane-use control signals are generally more effective than signing and for this reason their use is steadily increasing.

REFERENCES

1. *Traffic Control Devices Handbook*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1983.
2. *Manual On Uniform Traffic Control Devices*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1978.
3. Dudek, D. L., et al. *Human Factors Requirements for Real-Time Motorist Information Displays: Vol. 1 - Design Guide*. FHWA-RD-78-5. Texas Transportation Institute, September 1978.
4. Duff, J. T. "Accomplishments in Freeway Operations Outside the United States." *Highway Research Record 368*. Highway Research Board, 1971.
5. Bender, L. E. "Use of Changeable-Message Signs by Port Authority." *Highway Research Board Special Report 129*, Highway Research Board, Washington, D.C., 1971.

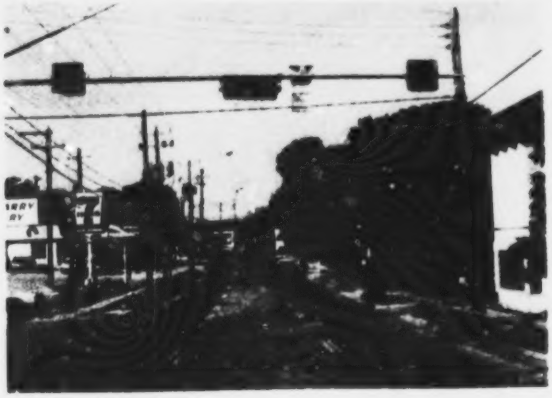


Figure 9.15. Lane-use control signals

Source: Reference (*25*)

6. Weckesser, P. M., and K. W. Dodge. "Efficient Use of a Busy Roadway." *Traffic Engineering*, April 1976.

7. Saxton, L., and C. Schenck. *Diversion and Corridor Control Systems in Western Europe.* Report No. FHWA-RD-77-69. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., June 1977.

8. Dorsey, W. *Variable Message Signing for Traffic Surveillance and Control — A State-of-the-Art Report.* Report No. FHWA-RD-77-98. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., January 1977.

9. Dudek, C. L., et al. *Human Factors Requirements for Real-Time Motorist Information Displays: Vol. 1 - Design Guide.* Report No. FHWA-RD-78-5. Texas Transportation Institute, September 1978.

10. Dudek, C. L., et al. "Changeable Message Signs." *NCHRP Synthesis of Highway Practice Report 61.* Transportation Research Board, February 1979.

11. Mammano, F. J. "Driver Information and Motorist Aid Hardware." *Proceedings.* International Symposium on Traffic Control Systems. Report No. UCB-ITS-P-79-2. Institute of Transportation Studies, University of California, August 1979.

12. Dunn, Walter M.; L. D. Powers; and P. Love. "The Integrated Motorist Information System: An Examination of Three Tradeoff Studies." *Proceedings.* International Symposium on Traffic Control Systems. Report No. UCB-ITS-P-79-2. Institute of Transportation Studies, University of California, August 1979.

13. Grover, Albert L. "Bulb Matrix Changeable Message Signs — Operational Characteristics." AASHTO Subcommittee on Communication and Electronic Applications for Highways, Los Angeles, California, November 1973.

14. Mammano, Frank J. "CB Motorist Aid — State of the Art." *Public Roads*, Vol. 44, No. 3, December 1980.

15. Spica, Frank M. *Project BEAR: One Year Evaluation.* Michigan Department of State Highways and Transportation, December 1980.

16. Dudek, Conrad L., and James P. Carvell. *Feasibility Investigation of Audio Modes for Real-Time Motorist Information in Urban Freeway Corridors.* Dallas Freeway Corridor Study, Report RF953-8. Texas Transportation Institute, April 1973.

17. Mammano, Frank J. "Assessment of Status and Trends In Motorist Aid Communications." Report No. FHWA - RD-83-098. Federal Highway Administration, Washington, D.C., April 1983.

18. Roper, D. H.; R. J. Murphy; and R. F. Zimowski. *Alternate Route Planning: Successful Incident Traffic Management.* Transportation Research Board Special Report 153, 1975.

19. Turnage, Howard C. "Highway Advisory Radio." *Proceedings.* International Symposium of Traffic Control System. Report No. UCB-ITS-P-79-5. Institute of Transportation Studies, University of California, August 1979.

20. Turnage, H. C. *Highway Advisory Radio Guide.* Atlantic Research Corporation. Report No. FHWA-RD-80-166, May 1981.

21. Atlantic Research Corporation. *Automatic Audio Signing, Vol 1 - Executive Summary.* Federal Highway Administration, Office of Research and Development, Washington, D.C., November 1983.

22. Dudek, Conrad L., and R. Dale Huchingson. *Manual on Real-Time Motorist Information Displays.* Federal Highway Administration, Washington, D.C., 1984.

23. Winko-Matic Signal Company, Avon Lake, Ohio, 1984.

24. Traffic Control Systems Company, Colorado Springs, Colorado, 1984.

25. U.S. Department of Transportation, Federal Highway Administration.

26. California Department of Transportation (Caltrans).

27. *Traffic Control Systems Handbook.* U.S. Department of Transportation, Federal Highway Administration, June 1976.

10. SELECTION OF A SYSTEM

CONTENTS

Section *Page*

10.1 INTRODUCTION 10.3

10.2 FEDERAL-AID REQUIREMENTS 10.3
  Policy and Eligibility 10.3
  Traffic Engineering Analysis 10.3
    Preliminary Analysis 10.3
    Alternative Systems Analysis 10.4
    Procurement and System Startup Analysis 10.4
    Special Features Analysis 10.4
    Analysis of Laws and Ordinances 10.5
    Operations Plan 10.5

10.3 SYSTEM SELECTION PROCESS 10.5
  Definition of System Requirements 10.5
  Identification of Alternative Systems 10.5
  Evaluation of Alternative Systems 10.6
    Utility-Cost Analysis 10.6
    Benefit-Cost Analysis 10.6
  Selection of Best System 10.8

REFERENCES 10.10

10. SELECTION OF A SYSTEM

10.1 INTRODUCTION

Significant advances have been made in traffic control systems technology during the past decade. Today, the demonstrated effectiveness and reliability of advanced traffic control systems has encouraged their widespread acceptance. As a result of new hardware and control techniques, agencies considering traffic control system improvements are offered a wide range of choices with respect to hardware and operational features. Making an appropriate selection from these available alternatives is important — not only because the use of public funds is involved — but because the choice will have a far-reaching impact on system users on a daily basis for an extended period of time.

A system selection *process* is considered necessary to encourage the objective consideration of alternatives in a structured, rather than subjective, manner. Further, the structured decision approach has been found to generate a sense of commitment to the choice among participating agencies, individuals, and disciplines which contribute to successful system implementation.

In the following material, a system selection process is described which focuses on recently developed Federal-aid requirements and relates these requirements to a process which has application regardless of funding source. The reader is also referred to three specific references which deal with the selection of control at individual intersections (*1*), urban street systems (*2*), and freeways (*3*).

10.2 FEDERAL-AID REQUIREMENTS

As a result of funding participation by the Federal Highway Administration (FHWA) and their active role in observing the planning, design, implementation, and operation of traffic control systems, significant experience has been accumulated with regard to system success and failure. In April 1984, in an effort to consolidate this information in a form usable to all those involved in traffic control systems projects, the Federal-aid Highway Program Manual (FHPM) was revised with respect to traffic surveillance and control systems. The full text of these requirements is included as Appendix A (*4*). The basis for these requirements is founded in control systems experience without regard for the funding source. In other words, the requirements have equal application for the planning, design, and implementation of control systems using only local funds as they do for projects funded with Federal-aid funds. The following material describes the specific elements of these FHPM requirements and the selection process which they support.

Policy and Eligibility

Traffic surveillance and control projects are recognized as an integral part of Federal-aid highway construction, and all phases of such projects are considered eligible for funding with appropriate Federal-aid highway funds. This statement of policy is important because it provides credibility for the relative importance of control system elements in relation to other highway construction elements. Further, the critical area of system startup is defined as fully eligible for Federal-aid funding.

Another critical factor is addressed under eligibility — the ability to operate and maintain the system. Experience has shown that an early commitment to provide adequate personnel and budget resources for operations and maintenance is a key factor in the successful utilization of systems. Because Federal-aid funds are not available for those ongoing expenses, the local agency must be aware of the requirement and committed to its satisfaction.

Traffic Engineering Analysis

In planning for traffic surveillance and control system improvements, a feasibility study consisting of multiple predesign study elements is generally conducted. Its scope and detail is generally influenced by the type and scope of the project being considered. For example, predesign studies for an arterial control system of 6 intersections are different than those needed for an areawide freeway surveillance and control system. The traffic engineering analysis should contain the following basic elements:

Preliminary Analysis. The preliminary traffic engineering analysis provides for a detailed examination of the present situation including an identification of the problem which must be addressed and the present resources available. Specific factors include:

- Area to be controlled — A control system may be planned for implementation in stages. What are the current and long-term needs?
- Transportation characteristics — Traffic flow data may be required to determine the characteristics of the system to be controlled. Factors of significance include: volumes, turning movements, speeds, number of buses, actuated versus pretimed control, topographic factors (i.e., grades), and proposed new roadway facilities.
- Existing systems resources — Certain elements of an existing system may be appropriate for continued use. Elements to be evaluated include: controllers, detectors, interconnect cables, and conduit systems. Of particular interest is the staff (number and capability), equipment and facilities, and budgetary commitment to operations and maintenance. An evaluation should also be made of the ability of these resources to accommodate changes in system requirements.
- Objectives of the system — Based on an examination of the current situation, the problems to be solved will be identified — leading to a specific definition of what the system must do. In this way, specific system goals can be defined, against which alternative systems can be measured.

This preliminary analysis phase simply provides for the accumulation of meaningful data for future use in analysis and decision-making.

Alternative Systems Analysis. The analysis of alternative systems implies two requirements — (1) that alternatives do exist, and (2) that some analysis process is available for use. As indicated in Chapter 2, there is a wide range of control system options ranging from the Basic System to Sophisticated Systems. Further, such systems are available in a number of forms, including manufacturer-packaged systems, user-tailored systems, and custom-built systems. Choosing from these available alternatives requires a critical self-examination of perceived system needs along with an in-depth consideration of life-cycle costs and performance issues. Some of the specific analysis criteria are as follows:

- Performance ability — Matching a control system's capabilities to a set of identified agency requirements is perhaps the most crucial elements of the system selection process. Performance ability is frequently expressed in terms of traffic operations requirements, equipment reliability and adaptability, and ease of implementation.
- Implications on personnel and budget — The capabilities of existing staff, maintenance facilities, and willingness to commit to ongoing budget requirements have a definite impact on control system decisions. Total replacement of electromechanical local controllers with microprocessor-based controllers, for example, would create a need for extensive training and could cause serious turbulence in the workforce.
- System costs — Initial system cost is the big item that captures much attention. However, it is only one element of cost that should be considered. A cost analysis that takes into account the full system life-cycle costs over an assumed period of use is necessary. In this way, annual recurring costs for maintenance and operation, as well as special training costs, can be considered along with system first-cost. It is also necessary to determine the incremental costs associated with adding some special feature to the control system.
- System benefits — System improvements are expected to produce benefits in terms of reduced delay, reduced travel time, reduced accidents, decreased fuel consumption and emissions, and other factors. Most of these are quantifiable and can be expressed in monetary terms. Others are less quantifiable and must be expressed by some proxy value which approximates its value or benefit. A specific utility-cost approach is briefly described in a following section of this chapter.

Procurement and System Startup Analysis. Chapter 11, Design and Implementation, describes the procurement options available for consideration. These include the traditional engineer/contractor approach and the systems manager approach — both of which have been used with success. System startup concerns the planning necessary to have a smooth transition from old to new control, including traffic handling during construction, timing plan and data-base preparation, and acceptance testing. Each of these items is discussed in Chapter 11, but are also important elements of the predesign system planning process. It is also instructive to note that flexibility exists in Federal-aid requirements sufficient to accommodate the special needs of systems procurement. More restrictive requirements are generally imposed by state and local agencies inexperienced in such procurements.

Special Features Analysis. Each agency with responsibility for traffic control systems represents a unique entity with no two being exactly alike. As a result, the traffic control system needs of such an entity are likely to also express some unique requirement. However, few are truly new, having never been encountered. Rather, most are simply situations encountered with less frequency, but situations for which some control system experience exists. Including these features in a control system should be done only on the basis of established need and favorable analysis in terms of incremental costs and benefits.

Analysis of Laws and Ordinances. Effective system operation may depend in part on motorist compliance and enforcement to ensure compliance. Just as there must be a legal basis for the use of traffic control devices, there may be a need to revise local laws and ordinances. For example, many local traffic codes may not address high-occupancy vehicle (HOV) lanes on freeways. A detailed analysis of laws and ordinances is a legitimate element of predesign studies.

Operations Plan. Documenting the analysis and decisions reached as part of the traffic engineering analysis is the final step. The resulting operations plan then becomes the foundation of agreement for system design, funding, procurement, construction management, system startup, and operations and maintenance. Having a commitment to the operations plan is a requirement for the authorization of Federal-aid highway funds. Even if that were not required, such commitment is necessary for successful system performance.

10.3 SYSTEM SELECTION PROCESS

The above discussion provides valuable insight into the essential elements pertaining to the selection of an appropriate signal system. In the following material, the focus is on the *process* used to structure the analysis, which leads to a consensus agreement for a specific control system approach. The process contains the following four sequential steps:

- Definition of system requirements
- Identification of alternative systems
- Evaluation of alternative systems
- Selection of desired approach

Definition of System Requirements

As described in Chapter 2, the two conditions which focus attention on a need to install or upgrade traffic control systems are (1) traffic growth or changes in traffic characteristics which impose control requirements beyond the capability of the existing system, or (2) mechanical/physical obsolescence of equipment which results in degraded and inefficient on-street operation. In either case, there is a specific need that the control system must fill. Identification of that need does not lend itself to a cookbook approach. Rather, it is a design process requiring the application of experience and detailed examination of conditions, capabilities, desires, and commitments. This definition of what the system must do is an important element of the system selection process.

The definition of system requirements by a single individual or outside agency is inappropriate. A structured approach involving multiple interests and agencies, perhaps with outside guidance, is preferred. With this approach, a project team, composed of individuals with management, planning, operation, and maintenance responsibilities is formed to guide the project from concept to reality. Multiple affected agencies can also be included to enhance jurisdictional cooperation during implementation and operation. Working in a common forum, this project team can develop specific system requirements which reflect the vested interests of affected groups, but with those positions refined through group interaction.

Certain ones of these requirements are absolutes — they must be provided. For example, the system must control X number of intersections. Other requirements may be desired but not be an absolute requirement — that is, it may be met with varying degrees of satisfaction. A requirement for equipment interchangeability might fit this category. Project team activity would be expected to identify these requirements and rank them into mandatory, very important, nice to have, and not necessary categories. This consensus definition of system requirements becomes the measure against which all alternative systems are compared.

Identification of Alternative Systems

A wide range of traffic control system alternatives exists, ranging from the basic to a sophisticated system as described in Chapter 2. The dynamics of the market place dictate that there will be constant change in systems offered and system capabilities. Manufacturers attempt to develop systems which have widespread appeal. Users experiment and develop unique approaches, and research produces evolutionary, and sometimes revolutionary, advances. The point is, the identification of alternative systems is a constantly changing arena of activity which involves talking with system manufacturers, system users, systems houses, consultants, researchers, and interested individuals. No individual or agency has all available information at hand, and only one summary document of available systems has been prepared (*5*).

Rather than concentrate at this point in the system selection process on individual available systems, it may be beneficial to consider groups of system *approaches*. For example, the standard products of manufacturers which have similar capabilities could be considered as one approach. Time-based coordinators could be another, and the most sophisticated custom designed system another.

In this way, a limited number of alternative system *approaches* may be considered.

Evaluation of Alternative Systems

The system selection process can be visualized as a 2-step process:

- Initial screening of the broad spectrum of possible systems
- Detailed comparison of the remaining alternatives and final selection based on a comprehensive analysis of system costs and benefits

This refined analysis of control system alternatives typically includes the following sequence of events:

- Estimating benefits or utilities for each alternative
- Estimating costs of each alternative
- Performing comparative analysis
- Selecting the system shown to offer the most potential

A wide variety of techniques have been used for the comparison of costs and benefits of alternative systems. Among these, two which have gained widespread use in the traffic control field are the following:

- Utility-cost analysis
- Benefit-cost analysis

Utility-Cost Analysis. Probably the most commonly applied technique is the utility-cost analysis, in which a utility measure is used as a proxy value for a system benefit (*2, 6*). The utility-cost factor for a particular system is simply the sum of the system utilities divided by the sum of the system costs.

In an earlier section of this chapter, the definition of systems requirements was discussed, where certain requirements are absolutes while others may be satisfied to varying degrees. Each of these requirements may be given a relative weight indicating its importance in this jurisdiction, thus forming the basic scale against which alternative systems may be measured.

The computational procedure used to rate each alternative system against these specified requirements is illustrated in Figure 10.1. There, the ability of each alternative system to meet each requirement is rated on a scale of 0 to 10, with 0 indicating that the requirement is not satisfied at all and 10 indicating total satisfaction. This internal rating scale is simply a measure of how well this alternative system satisfies this requirement. Combining the individual rating with the relative weight gives a measure of the utility value for that requirement. The sum of all individual utility values gives an overall utility rating for each alternative system. Example weighted system requirements are shown in Tables 10.1 and 10.2.

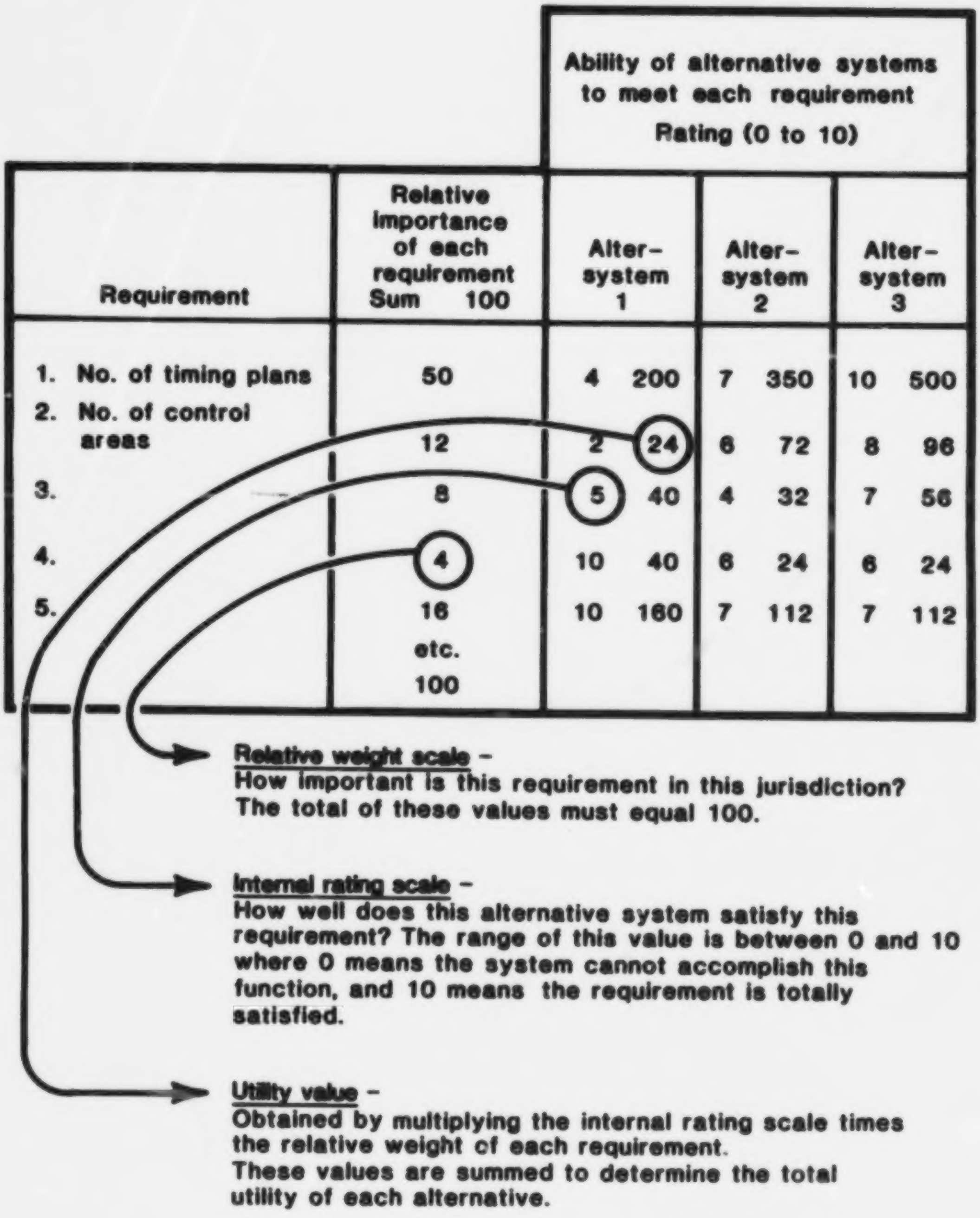
The other factor, cost, used in the utility-cost analysis should reflect estimates of both one-time costs and recurring costs over some identified time period. Since these funds are expended at different times over the analysis period, a present worth analysis is generally used to convert all costs to a present value. In this way, all systems are compared on an equal basis.

Computation of the utility-cost of each alternative system is then a simple step using an equation which contains the system's good features (utility values) in the numerator and its bad features (costs) in the denominator. Therefore, it may be concluded that the best system is the one with the largest utility-cost ratio. However, the danger of such a conclusion is that a simple, cheap system with both low utility and low cost might have the same ratio as a sophisticated, affordable system with a high utility that satisfies all of the defined requirements.

To avoid this conclusion, the results of the utility-cost analysis are plotted as shown in Figure 10.2. The slope of the line indicates the utility-cost ratio, and the endpoint of the line represents the individual values of utility and cost for each alternative. In this manner, systems with equivalent utility-cost ratios, such as Systems 1 and 2, can be readily compared. Notice also that the range of uncertainty associated with costs and utilities is reflected by the rectangle at each point. Further, notice that Systems 4 and 5 can be excluded from further consideration for two practical reasons — first, they fall beyond the range of acceptable cost, and second, they provide less utility than that provided by System 3 at a lower cost.

Benefit-Cost Analysis. The benefit-cost ratio offers a second technique for comparing alternative systems. This technique uses benefits and costs that are compared in much the same manner as the utility-cost analysis. The primary difference is that system benefits are expressed in monetary terms rather than as a utility rating. Simulation models and offline optimization programs are frequently used to determine the expected benefits, generally expressed in terms of time and fuel savings to motorists.

The advantage of the benefit-cost ratio is that the system benefits are expressed as dollar savings to motorists and can be readily understood by the public. The disadvantage is that it is difficult to quantify in monetary terms many of the intangible benefits of sophisticated signal systems.



Requirement	Relative importance of each requirement Sum 100	Ability of alternative systems to meet each requirement Rating (0 to 10)					
		Alter-system 1		Alter-system 2		Alter-system 3	
1. No. of timing plans	50	4	200	7	350	10	500
2. No. of control areas	12	2	24	6	72	8	96
3.	8	5	40	4	32	7	56
4.	4	10	40	6	24	6	24
5.	16	10	160	7	112	7	112
	etc.						
	100						

Relative weight scale –
How important is this requirement in this jurisdiction? The total of these values must equal 100.

Internal rating scale –
How well does this alternative system satisfy this requirement? The range of this value is between 0 and 10 where 0 means the system cannot accomplish this function, and 10 means the requirement is totally satisfied.

Utility value –
Obtained by multiplying the internal rating scale times the relative weight of each requirement. These values are summed to determine the total utility of each alternative.

Figure 10.1. Example of utility calculations

Source: Reference (*2*)

Table 10.1. Utility measure weights

Utility Measures	Range	Normalized Average		Weight
Adaptability (Rating 16.0)				
Incorporation of new control logic	10-60	28.4		4.6
Accommodation of traffic pattern shifts	10-50	32.8		5.2
Adjustment to physical changes	20-40	28.3		4.5
Incorporation of nontraffic control functions	10-15	10.5		1.7
		100.0	Subtotal	16.0
Areawide Traffic Management (Rating 14.9)				
Special traffic functions	15-30	24.5		3.6
Special events	10-40	22.8		3.4
Coordinated control of all signals	40-70	52.7		7.9
		100.0	Subtotal	14.9
Implementation Characteristics (Rating 14.4)				
Implementation in phases on priority basis	25-40	36.7		5.3
Minimal degree of implementation complexity	10-25	19.5		2.8
Minimal impact on traffic	10-30	18.3		2.6
Using of existing equipment	10-40	25.5		3.7
		100.0	Subtotal	14.4
Performance Monitoring and Operator Interface (Rating 14.1)				
Dynamic display map	25-50	33.1		4.7
Operator console	20-45	32.6		4.6
Data logging and MOE analysis	20-50	34.3		4.8
		100.0	Subtotal	14.1
Reliability (Rating 19.5)				
Failsafe and backup capability	10-45	26.1		5.1
Hardware failure monitoring and reporting	20-30	22.2		4.3
Software reliability	10-50	24.5		4.8
Ease of maintenance	15-50	27.2		5.3
		100.0	Subtotal	19.5
Traffic Operation (Rating 21.1)				
Adequate number of timing plans with multiple zones	10-25	16.1		3.4
Isolated, arterial, and network control	10-30	17.2		3.6
Coordination of adjacent zones	10-40	18.4		3.9
Local intersection optimization	15-35	25.0		5.3
Selection of timing patterns by manual, TOD, or TR	10-35	23.3		4.9
		100.0	Subtotal	21.1
	TOTAL			100.0

Source: Reference (7)

In practice, benefit-cost analyses perhaps have their greatest application in answering the question, "Is the recommended system or improvement economically justified, and, if so, how does this improvement compare with other construction related improvements?" Utility-cost analyses, in contrast, are more appropriately used in choosing among viable alternatives.

Selection of Best System

Total dependence on the utility-cost or benefit-cost analysis results for system selection decision is cautioned. Rather, the primary strength of the analysis approach lies in its orderly consideration of all factors which influence system preference. Utilization of the analysis process

Table 10.2. Example freeway goals and subgoals

Goals and Subgoals	Weight	Percentage
1. Traffic operations		
Reduce freeway delay to the motorist	(70)	44
Maintain level of service D	(50)	31
Reduce stop-and-go congestion	(40)	25
		100
2. Safety (4 percent)		
Reduce freeway accidents	(100)	57
Reduce ramp/merging accidents	(75)	43
		100
3. Implementation (2 percent)		
Disruption of traffic during construction	(60)	46
Time frame of installation	(30)	23
Training of operational personnel	(40)	31
		100
4. Operating factors (14 percent)		
Equipment simplicity	(60)	38
Level of equipment maintenance	(100)	62
		100
5. Freeway management (23 percent)		
Provide management mechanism	(50)	9
Accommodate future demands (expansion capability of equipment)	(80)	14
Redistribute delay/demand	(30)	6
Defer capital improvement	(35)	6
Provide traffic operation surveillance	(60)	11
Improve accident/incident response	(40)	7
Facilitate data collection	(80)	14
Provide driver information	(40)	7
Coordinate with corridor signal systems	(75)	13
		100
6. Operational efficiency (23 percent)		
Responsiveness to flow instability	(60)	16
Responsiveness to incidents	(50)	14
Variation of peak start/end times	(50)	14
Responsiveness to fluctuating demand	(30)	8
Adjustment of metering rates	(100)	27
Responsiveness to traffic pattern changes	(75)	21
		100

Source: Reference (*3*)

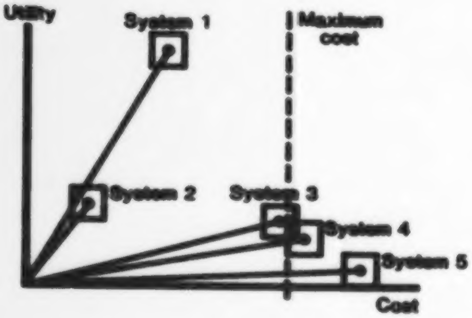


Figure 10.2 Utility-cost comparison of alternative systems

provides a basis and framework for communication among decision-makers who possess varied technical and interest backgrounds. The use of the results as an indicator of *system preference*, rather than as an absolute evaluator, is to be preferred.

As indicated in Chapter 2, the *best* system is the one which comes closest to matching an identified set of agency requirements, and for which a consensus commitment has been made to dedicate those resources necessary to make it work.

REFERENCES

1. Tarnoff, P. J., and P. S. Parsonson. *Selecting Traffic Signal Control ct Individual Intersections.* National Cooperative Highway Research Program Report 233, Transportation Research Board, June 1981.

2. Stout, T. L., et al. *An Approach for Selecting Traffic Control Systems.* National Cooperative Highway Research Program, Transportation Research Board, Project 3-18(3) Final Report, March 1977.

3. Blumentritt, C. W., et al. *Guidelines for Selection of Ramp Control Systems.* National Cooperative Highway Research Program Report 232, Transportation Research Board, May 1981.

4. *Federal-aid Highway Program Manual.* Vol. 6, Chap. 8, Sec. 3, Subsection 4. Traffic Surveillance and Control, Transmittal 376, April 2, 1984.

5. Basu, S., and J. R. Wroble. *Computerized Signal Systems: Overview and Product Summaries.* Report No. FHWA-TS-82-218, U.S. Department of Transportation, Federal Highway Administration, September 1982.

6. Kay, Jack L. "Cost Utility Analysis Procedure for Evaluating Alternative Sytems." *Compendium of Papers.* Institute of Transportation Engineers, 42nd Annual Meeting, New York City, 1972, pp. 137-144.

7. PAWA, Incorporated. *Las Vegas Urban Area Traffic Control System Study.* State of Nevada Department of Highways, 1979.

11. DESIGN AND IMPLEMENTATION

CONTENTS

Section *Page*

11.1 INTRODUCTION 11.3

11.2 SYSTEM IMPLEMENTATION 11.3
Systems Management 11.3
Design Plans and Specifications 11.3
Construction Phase 11.3
Training, Debugging, Documentation, Evaluation, Turnover 11.4

11.3 PROCUREMENT APPROACH 11.4
Engineer (Consultant)/Contractor Approach 11.4
Systems Manager Approach 11.5
A Two-Step Procurement 11.5
Comparison of Approaches 11.6

11.4 DESIGN PLANS AND SPECIFICATIONS 11.6
Design Plans 11.7
Specifications 11.7
Sources of Specifications 11.7
Closed vs. Open Specifications 11.7
Functional vs. Material Specifications 11.8
Standard Specifications 11.8
Contract Documents 11.8
Invitation to Bid 11.8
Instructions to Bidders 11.8
Bid Proposal 11.8
Bonds 11.8
Agreement 11.9
Conditions 11.9
Contractor Qualifications 11.9
Precedence 11.9
Technical Specifications 11.9
Definition of Terms 11.9
Installation of Traffic Signals 11.9
Specifications for Materials and Equipment 11.10

11.5 DELIVERABLE SERVICES 11.11
Systems Management 11.11
Documentation 11.11
Training 11.11
Startup Assistance 11.12
Warranties/Guarantees 11.13
Maintenance 11.13

339

Section *Page*

System Acceptance Test 11.14

11.6 PROJECT MANAGEMENT 11.14
- Contract Administration 11.16
- Scheduling 11.16
  - *Project Evaluation and Review Technique (PERT)* 11.16
  - *Critical Path Method (CPM)* 11.16
  - *Bar Charts* 11.17

11.7 IMPLEMENTATION PITFALLS 11.17
- Inexperienced Contractors 11.18
- Construction Management 11.19
- Timing Coordination during Construction 11.21
- Data Base Development 11.21
- Insufficient Staff for Operations and Maintenance 11.21
- Utility Coordination 11.21
- Planned Use of Untested Facilities or Techniques 11.22
- Alienation of Maintenance Staff 11.22

REFERENCES 11.22

11. DESIGN AND IMPLEMENTATION

11.1 INTRODUCTION

The purpose of this chapter on traffic control system design and implementation is described in the following four ways:

- To place the system design, procurement, and installation tasks in perspective with respect to total system planning and implementation
- To describe alternative approaches used in the procurement of systems, including contractor selection
- To describe the various elements of the design process, with particular emphasis on the contents of bid documents
- To describe elements of a system installation and project management approach

The material presented in this chapter is intended to be applicable to virtually any size or complexity of a traffic control system, from a simple arterial system to a highly sophisticated computer-based system.

Prior to the actual beginning of a traffic control system design, a number of actions should already be completed, including the following:

- Conducting traffic operations studies to define traffic control needs that must be met
- Defining system goals
- Identifying alternative systems (hardware and software)
- Selecting the type of system appropriate for this specific application

11.2 SYSTEM IMPLEMENTATION

System implementation includes the following major elements:

Systems Management

The application of systems engineering techniques to a project can be termed "systems management." The total and continuous planning of a project from inception to phase-out can be defined as "systems engineering" (*1*). Both are interdisciplinary activities which draw on the talents of traffic engineers, mathematicians, computer designers, software designers, programmers, and such other specialists as the project might require, as shown in Figure 11.1.

Cleary states that inherent in the systems management process is the planning and management of both personnel and budget of each and every step of the process with an objective of on-time with in-budget delivery of a system designed to meet the client's requirements (*1*).

Design Plans and Specifications

The first step in the systems management process following the system planning and analysis phases is the preparation of design plans and specifications.

This phase of the management process takes the preliminary plans and functional specifications of the project and transforms them into design documents around which a project can receive competitive bids and be implemented.

The completion of the design plans and specifications marks the beginning of the project management process, which carries the project through the following steps:

- Procurement of the system components
- Construction of the system
- System training, debugging, and documentation; and acceptance testing and other deliverable services
- Turning the operating system over to the user

Construction Phase

The construction phase can make or break a project. In this phase, the system components are designed, manufactured, and installed. Construction also involves the testing and approval/disapproval of various components designed for the project. Unless the construction phase is properly managed, long delays may occur in the procurement and installation phases. Such delays can be costly to the client and the systems manager or contractor.

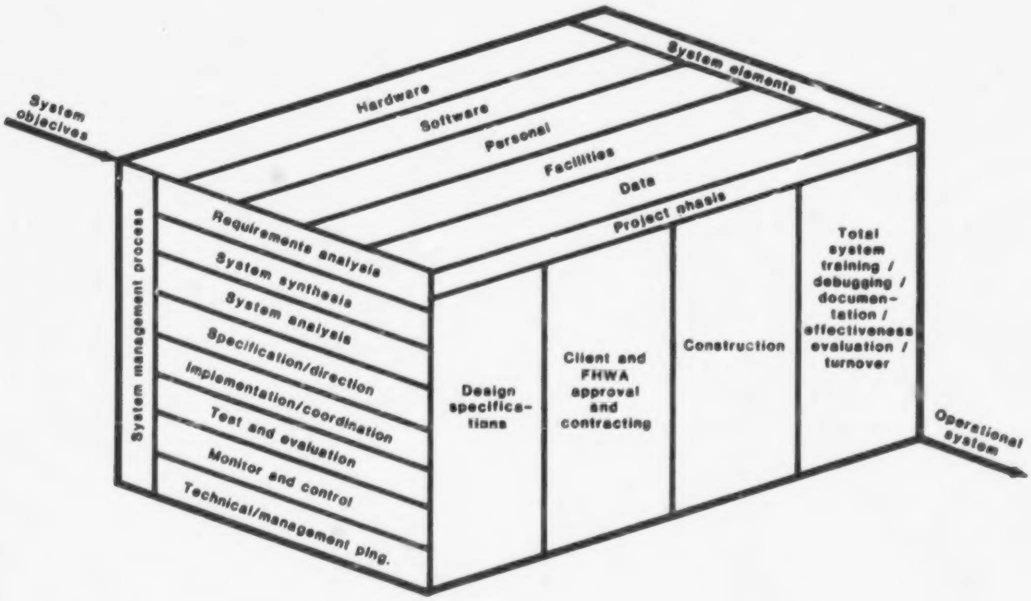

System objectives
Hardware
Software
Personal
Facilities
Data
System elements
Project phase
System management process
Requirements analysis
System synthesis
System analysis
Specification/direction
Implementation/coordination
Test and evaluation
Monitor and control
Technical/management plng.
Design specifications
Client and FHWA approval and contracting
Construction
Total system training / debugging / documentation / effectiveness evaluation / turnover
Operational system

Figure 11.1. Systems management matrix

Source: Reference (*1*)

Training, Debugging, Documentation, Evaluation, Turnover

This marks the final phase of the project and also prepares the project for final turnover to the client. In this phase, the systems manager (or the contractor) supervises system debugging, training of operational and maintenance personnel, documentation of system software, and evaluation of the effectiveness of the system in meeting the operational requirements.

11.3 PROCUREMENT APPROACH

At this point, all predesign and system feasibility studies will have been completed with a specific signal system type also selected as the most appropriate to satisfy the control system goals. Before proceeding further with detailed system design, the procurement approach and contracting procedures need to be established. Two basic approaches are possible — using a systems manager or an engineer (consultant)/contractor. Both of these, which have been used successfully, are described in the following sections:

Regardless of the approach chosen, the following two basic principles must be satisfied:

- Specifications must be developed by an organization separate from that supplying the hardware, bidding on the project, or installing the system.
- Competitive bid requirements must be followed in the procurement of all hardware and software items.

Engineer (Consultant)/Contractor Approach

The engineer (consultant)/contractor approach represents the more traditional procedure for contracting within the highway agency community. In it, the engineer (consultant) proceeds, on the basis of feasibility studies and system selection activities, to prepare the design plans, specifications, and estimates (PS&E) for the proposed system. The engineer may be either an agency employee or a consultant retained for that purpose. Completed PS&E are then issued to the contractor community, and bids are received in accordance with roadway/highway established practice. It should be noted that such established practice has evolved through years of use within each agency on other than control system projects. As a result, procedures may be included which are difficult or inappropriate to apply to control systems with hardware (tangible) and software (intangible) elements.

In this approach, the contractor bids on a single set of specifications and agrees to provide a total operating system, composed of hardware items and software, which is to be procured, installed, and integrated by his organization. Hardware items may be of his manufacture, and he may subcontract portions of the project — within the constraints imposed by the contract. The contractor is also responsible for all systems-integration tasks, documentation, and training. He may be responsible also for the development and implementation of timing plans and provision of system startup assistance.

The engineer (consultant) continues his activities during the system installation project by monitoring the contractor's progress, interpreting or clarifying plans and specifications, processing the contractor's technical submittals and payment requests, and coordinating activities with other agencies such as the utility companies or the control center architect. As previously indicated, all or part of the engineer's duties may be performed by the agency or by its selected consultant.

Systems Manager Approach

Kittides has defined a construction manager as "a professional agent, free of competitive bidding pressures, who furnishes a number of skills, primarily technical, economic, and managerial, throughout the planning, design, and construction phases of a project and who coordinates the activities of all other parties of the construction process" (*2*).

Although Kittides' definition applies primarily to the building construction industry, it can relate to the design and implementation of a traffic control system because the construction manager here is similar to the systems manager in a traffic control system project.

The systems manager approach requires the selection of a single firm (as systems manager) to be responsible, under an engineering services contract, for the system design, PS&E preparation, systems integration, documentation, and training. A procedure such as one used to select an engineering consultant is typically used to select a systems manager. Negotiated cost-plus-fixed-fee contracts are frequently used for system manager services.

To avoid conflicts of interest, the systems manager usually accepts a hardware exclusion clause which prohibits his supplying any of the hardware components of the system. However, most systems managers do provide the applications software package, including unique modifications tailored for the specific system.

In practice, the systems manager prepares detailed designs and PS&E for individual components or subsystems of the total system. The agency's normal bidding processes are then used to procure these individual subsystems or services, and the systems manager subsequently manages the testing and installation of the equipment. The systems manager also provides for the integration of all the hardware elements and the software in order to provide a total operating system.

A Two-Step Procurement

In the early days of computer-based control system implementation, several problems arose because of designer and contractor inexperience and unfamiliarity with computers, software, and digital data communications, as well as the sophistication of such large systems. In some cases, inexperienced contractors who were chosen through the low-bid process attempted control system projects without a clear understanding of the requirements or the risks imposed. During that period, the 2-step procurement procedure was initiated as a means of modifying the typical low-bid process to include a measure of contractor prequalification (*3*).

In the first step of this process, the system PS&E as prepared by the engineer (typically functional specifications) is submitted to all interested contractors, who are invited and encouraged to submit a technical design proposal. In this response, the prospective contractors respond to the specification by performing the following:

- Identify their technical experience and capabilities to perform work of this nature
- Provide staff capability data
- Describe their approach to performing the requirements of the project
- Describe major hardware subsystems (manufacturer and model with alternates) chosen for inclusion in the system
- Comment on schedule requirements

Cost data are specifically excluded from this submission. However, sufficient information is presented to form a defensible basis for contractor prequalification or rejection relative to the provisions and requirements of the specifications.

Following the initial step, a formal request for bid, perhaps with addenda to clarify issues or discrepancies revealed during this phase, is issued only to those prequalified contractors. The second step, then, becomes the typical advertise, bid, evaluate, and award process of the engineer (consultant)/contractor approach.

Comparison of Approaches

As previously indicated, these approaches and variations have been used with success. Baltimore was a pioneer user of the 2-step approach, as was Omaha. Dallas, El Paso, Tulsa, Tampa, Jacksonville, Broward County, Florida, and others have used the engineer (consultant)/contractor approach, while Los Angeles; Portland, Oregon; and the first phase of Dade County, Florida, have used the systems manager approach.

The primary differences between the two basic approaches are as follows:

- The systems manager fills a role that may be perceived as both engineer (preparation of subsystem PS&E) and software supplier. In the engineer (consultant)/contractor approach, these roles are clearly separated.
- The systems manager must use local agency procedures to procure individual hardware components and individual construction contractors through competitive bids — a process that can produce delays and additional problems. However, in the engineer (consultant)/contractor approach, the contractor may acquire equipment and services from his chosen sources.
- In the systems manager approach, a single firm is responsible for both the design and integration, which avoids controversies over design problems that may arise. However, for this approach as opposed to the contractor approach, there are no checks and balances in the development process other than those imposed through active agency participation.
- In contrast to the systems manager approach, the engineer (consultant)/contractor method uses two organizations, each of which is a specialist in a respective phase of the project. However, with two such organizations, difficulties in identifying responsibilities can occur.

Choice of the procurement approach also has an impact on the preparation of plans and specifications. Specifications developed under the engineer (consultant)/contractor approach will generally emphasize the functional characteristics of the equipment and impose operational and design constraints. They will describe *what* must be done but leave to the contractor, within constraints, *how* it must be done.

By contrast, the systems manager must develop detailed specifications that describe interface requirements, voltage levels, data rates, connector types, etc., in order to ensure their proper integration into a total system. It may also be necessary to procure major subsystems sequentially in order to ensure their compatibility.

This description of the two basic procurement options has attempted to treat each as a separate approach. Obviously, they can be and have been used in various combinations and mixes. In one such application, the local agency purchased new local controller assemblies and installed them using their maintenance staff. The agency then contracted for installation of underground conduits using the PS&E developed by a consultant, and finally selected a systems manager to implement a computer-based control system in space prepared by a separate department's architect and building contractor.

Without regard to the procurement approach selected, the success of a traffic control system ultimately depends on people. As clearly stated by O'Malley, "It cannot be overemphasized that regardless of the sophistication of the tools that we have to do the job, it is still people, whether it be individuals, private firms, or government agencies, that ultimately must work together to achieve success"(*4*). One common observation of operational systems is that the ones experiencing the greatest success are those in which a knowledgeable agency staff participated in all phases of the predesign, design, and implementation activities.

11.4 DESIGN PLANS AND SPECIFICATIONS

Construction contract documents are considered as tools for communication between the owner (purchaser, local government), and contractor (supplier). Properly prepared, they prevent disagreements and aid in project completion by clearly communicating what it is the owner wants done and by when.

The two principal elements of contract documents are plans (more properly called drawings) and specifications (*5*). Plans fill the role of defining the physical relationships of materials upon which the contract is based. Of a complementary nature, the specifications define the *quality and types* of workmanship and materials. Understanding the unique role of each of these documents not only will produce clarity, brevity, and consistency, but will also avoid redundancy. Otherwise, it is a temptation for the designer to cover the same requirement in both the plans and the specifications. Then, a hasty change in requirements produces inconsistency and misinterpretation because it was changed in one place and not another.

In the following sections, typical contents of plans, specifications, and contract documents are described.

Design Plans

The design plans indicate the manner in which the components of a control system are to be constructed and installed. Such plans for a traffic control system project may include the following:

- Title sheet — Showing name, location and scope of project
- Summary of quantities — Showing material and equipment quantities
- General notes — Inclusion of general notes in design plans is frequently used to call special attention to critical requirements of the project and ensure that they are not overlooked because of being buried within the specifications. Care must be taken to avoid conflicts with specifications.
- Intersection layout — Giving an outline of pole, signal, and conduit locations and other pertinent intersection information
- Conduit, cable, and signal head tables — Indicating the number designation of the run, size of conduit, size and number of cable or cables in the conduit, and the approximate length of the conduit; with signal head tables outlining the type of signal head, the size and type of signal lenses, and the type and size of pole on which they are mounted
- Intersection phasing diagram — Indicating how each intersection is to be phased to include vehicle and pedestrian intervals
- Wiring diagram — Indicating color coding of wiring from local controller cabinet to signal heads and from master controller to local controllers; with wiring diagrams an optional item valuable, if adhered to, as a permanent record for maintenance purposes
- Intersection and system timing plans — Illustrating interval timing, offsets, and other intersection timing
- Construction design drawings — Showing minimum requirements for construction dimensions and materials for foundations, poles, controller cabinets, detectors, signal heads, etc.
- Traffic control plan — Indicating how traffic is to be handled during construction, particularly addressing the need for continuous interconnected operation of existing signals
- Details of barricades, detour layouts, and signing — Illustrating the construction phase of the project
- Diagram of underground utilities — Showing details of location
- Standard plans — Possessed by each agency, generally providing numerous standard drawings of frequently encountered details already approved for use in situations which are applicable to the project

These items provide valuable information to the contractor and equipment supplier for the preparation of a project bid. In addition to their value in the preparation of bids, these documents also serve as control elements during a project's construction.

For the details of each of these elements of design plans, see the *Manual of Traffic Signal Design* (*6*) prepared through the Institute of Transportation Engineers (ITE).

Specifications

Since traffic signal control systems are purchased and installed on a competitive bid basis, specifications are needed. These specifications will spell out the minimum acceptable requirements for the traffic control system's equipment and materials, as well as the manner in which the system should be installed. Without adequate specifications, the equipment, materials, and installation of the system may be inferior and thus create maintenance problems for the purchaser of the system. Substandard specifications can often lead to the use of low-cost, inferior equipment and materials on a project.

Sources of Specifications. Good specifications are often difficult to prepare, because of the numerous and varied types of equipment and materials that should be covered. It is virtually impossible for a traffic engineer to be fully aware of all the components of the various items of equipment and material that comprise a traffic control system, plus be able to specify their every detail. For this reason, existing specifications which have proved to provide good equipment and materials are often used in their entirety or modified to fit the particular need or needs of the purchaser. Several good sources for equipment and materials specifications are the following:

- Federal Highway Administration (FHWA), Office of Traffic Operations
- Institute of Transportation Engineers (ITE)
- International Municipal Signal Association (IMSA)
- National Electrical Manufacturers Association (NEMA)
- Other cities
- State highway or transportation departments

Closed vs. Open Specifications. It is important that the specifications be written in such a manner that high-quality equipment and materials will be required.

However, care should be taken to ensure that specifications are not written around a particular manufacturer's equipment or material so as to prohibit competitive bids from several manufacturers. Closed specifications, those that specify a particular manufacturer's equipment may not meet the intent of Federal, state, or most local procurement laws, and will more than likely lead to high, noncompetitive bids. Open specifications will allow a competitive number of bidders on equipment and materials, usually resulting in lower bids.

Functional vs. Material Specifications. Functional specifications describe what the system must do, whereas material specifications describe in detail the individual features or capabilities of each component or subsystem. As previously indicated, the procurement approach selected will influence the type of specification which should be prepared. Under the systems manager approach, for example, items such as voltage levels, communications modulation techniques, connector pin assignments, etc., must be specified in detail to assure the ability to integrate the components into a total system.

By contrast, specifications prepared by the engineer/contractor approach tend to be more functionally oriented, ideally specifying end result requirements and placing the responsibility on the contractor to provide an integrated system. Integration requirements should be thoroughly specified through acceptance-test types of criteria where certain subsystems are not a part of the contract, such as when city-installed cable, leased telephone, or shared use coax cable is used.

Standard Specifications. Standard specifications, as referred to only by name, number, and date in the project specifications, are also made a legal part of the contract. Examples of such standard specifications are the following:

- Concrete or drilled shaft specifications which have previously been adopted by the city or State and which are available for purchase by the public
- Standard specifications for materials testing such as the American Society for Testing Materials (ASTM)

The design engineer should be thoroughly familiar with standard specifications and be consistent with them in preparing project designs.

Contract Documents

Together with design plans and specifications, contract documents form the complete legal package of documents to which the contractor must conform. Contract documents typically contain the following items:

- Invitation to bid
- Instructions to bidders
- Bid proposal
- Bonds
- Agreement
- Conditions to contract
- Qualifications

A discussion of each of these items follows.

Invitation to Bid. An invitation to bid is generally a 1-page document containing a brief summary of the project and its bidding and construction procedures. Its purpose is simply to advise prospective bidders about the existence of the project and to enable them to decide whether this is a project within their area of capabilities and interest. It further directs interested contractors to the source of bid documents should they be interested.

Instructions to Bidders. Instructions to bidders are intended to tell each bidder how to prepare a bid in order that all bids received are in the same format for ease of comparison and evaluation. The role of this document is to systematize the content of bid forms, and its contents should be limited to those items which contribute to that end. Specifically, the issue of exclusions and substitutions by a bidder is dealt with in this document in order to assure comparability of bids.

Bid Proposal. A bid proposal is designed to provide a uniform arrangement that facilitates comparison and equal consideration for awarding the contract. In the instructions, bidders are told what they must do. On the bid proposal form, they respond and quote their proposed price for doing it. Bid proposals, which should be addressed to the agency, should include general statements committing the bidder to having read the documents thoroughly and to being familiar with the site and the problems associated with producing the system as designed. The receipt of all issued addenda should be acknowledged by the bidder, and the signature(s) of individuals authorized to bind the bidder must be affixed.

Bonds. A bond is a legal document which binds someone else into the formal contract as a security that the bidder (or contractor) will perform as agreed. The following three types of bonds are in common usage:

- Bid bond — A bond posted by the bidder as an assurance that he will sign the contract if it is awarded to him, frequently required to be in an amount equal to about 10 percent of the base bid submitted
- Performance bond — A bond posted by the bidder to whom the contract is awarded as guarantee that he

will complete the project and not default on its completion; this bond is typically required in an amount which equals the full contract price

- Labor and materials payment bond — A bond posted by the successful bidder as guarantee that he will pay for all materials and labor used and will not leave the agency liable for liens against the completed system, with such a bond generally being required to cover the full contract price

Agreement. The agreement document is often mistakenly called the contract. Actually, the contract consists of all the contract documents, while the agreement is only one of those documents. The role of the agreement is to show the following five particular elements:

- Identification of the parties (who)
- Statement (perhaps by reference to another document) of the work to be performed (what)
- Statement of the consideration (how much)
- Time of performance (when)
- Binding signatures of parties

Conditions. The general conditions document is the fine print defining contractual relationships and procedures relative to the project. Most city and state agencies have established general conditions which apply to all their construction documents. Another source for applicable general conditions is published by the National Society of Professional Engineers (NSPE) (*7*). General conditions documents are normally printed in large quantities and issued as standard documents. But a characteristic of the traffic control system project is its individuality. Since it does not exactly fit the mold around which general conditions were standardized, a project's specific modifications are lumped into one document called supplementary conditions. One example of an item which should be covered in supplementary conditions is agency access to equipment during installation, such as to a computer master for purposes of data base development.

Contractor Qualifications. Contractors are typically required to be prequalified in order to receive project bid documents. This prequalification may take the form of a general review of submitted financial and experience data. Traffic control systems are specialized projects and require a level of expertise and experience that may not be widespread with the contractor industry. In this section of the contract documents, contractors should be advised of the minimum experience and qualifications necessary to submit a bid, as well as instructed as to the requirements for submitting special qualification data for review.

Precedence. With all these individual elements of a contract, a specific hierarchy of precedence should be defined in order to establish clearly which document governs in case of a conflict of requirements within the documents. As an example, the hierarchy (in decreasing order of control) could be as follows:

- Agreement
- Plans
- Special (technical) specifications
- Standard specifications
- Supplementary conditions
- General conditions

Technical Specifications

Technical specifications outline the specific requirements for materials and equipment, in addition to the methods by which they are to be installed and operated. These specifications, which form an integral part of the contract documents, should include individual specifications for major items of material and equipment, in addition to the methods of construction and installation. Such items as operating manuals, training, and software for digital systems should also be included.

The following major categories should be included as part of the technical specifications:

Definition of Terms. Words used frequently throughout the technical specifications should be defined, forming a leading section of the technical specifications. The definition of these items serves as a glossary, in that it sets forth the meaning of terms peculiar to the design plans, specifications, and other contract documents. Examples of terms that may be defined are the following:

- ITE — Institute of Transportation Engineers
- Traffic signal — Any power-operated traffic control device, except a sign or a flasher, by which traffic is warned or is directed to take some specific action
- Signal system — Two or more signal installations operating in coordination

Installation of Traffic Signals. The specification regarding the installation of traffic signals sets forth the detailed requirements for installation of the various items of material and equipment. It prescribes the methods by which the various items comprising the signal system are to be installed.

Certain items associated with the installation of traffic signals may be covered by other standard specifications (e.g., drilled shaft foundations, reinforcing steel) which have been adopted and published by the local governing authority. Standard specifications for roadway construction can normally be obtained from public works departments of cities or from the state highway departments. A reference, noting the name of the publication and the effective date, usually covers specifications for parts of the signal system not pertaining directly to the traffic signal installation.

Items covered under the installation of traffic signals technical specification should include, as a minimum, the following (*8*).

- General — The items covered by the specifications, the requirement for furnishing new, undepreciated stock, and the procedure for the substitution of materials and equipment
- Materials to be furnished by contractor — Details of what materials and equipment are to be furnished by the contractor and what materials and equipment are to be furnished by others
- Power connection — Method for furnishing power from source to controller assembly and specifications for power line
- Conduit — Methods for installing conduit, to include conduit approval by Underwriters' Laboratories, methods for joining conduit, and methods for testing the usefulness of an installed conduit
- Wiring — Methods for wiring controller cabinet, signal heads, and pole bases
- Grounding and bonding — Requirements for grounding and bonding signal housing, controller housing, signal common, and power service common
- Sealing — Requirements for sealing conduit to provide continuously sealed electrical circuit
- Concrete — Standard specifications for concrete and reinforcing steel
- Concrete foundation for controller cabinet and signal posts — Methods and requirements for digging, placing, finishing, and backfilling concrete foundations
- Paint and painting — Items to be painted, the type of paint, the number of coats, and the method of painting (e.g., baked-on, sprayed, etc.)
- Preservation of sod, shrubbery, and trees — Requirements for the replacement of damaged sod, and the protection of shrubbery and trees
- Removal and replacement of curbs and walks — Procedure for obtaining approval to cut curbs and/or sidewalks, and the method for their replacement
- Disposition of keys for controller cabinet and the instruction manuals for the control equipment) — Where keys and instruction manuals are to be delivered and the number of each required

Other items may be added to the technical specification for installation of traffic signals that will fit the particular needs of the subject control system.

Specifications for Materials and Equipment. The number of types of technical specifications required for materials and equipment will depend on the control system planned. For example, a control system may consist only of the installation of a master computer and interface (adapter) units at the local intersections. In this case, the technical specifications would include those for the master computer, the interface unit, and the installation of those items. Other control systems might consist of the installation of a master controller, the intersection controllers, the conduit, etc.

The following serves as a guideline for those items of materials and equipment which might require technical specifications:

- System master — May be a pretimed master, field-located arterial master, central computer, etc.
- Intersection controller — May be pretimed, actuated, volume-density
- Mast-arm pole assembly — To include mast-arm pole, base, and anchor bolts
- Pedestal pole assembly — To include pole, base, and anchor bolts
- Strain pole — Used for span-wire-mounted signal heads
- Signal heads — To include housing, doors, lenses, lamps, wiring, terminal blocks, terminal compartment, and mounting attachments, but with separate specifications for pedestrian signals
- Signal conductor — To include covering, color coding, and physical characteristics
- Signal cable — To include insulation, physical properties, electrical properties, color coding, and fillers
- Detectors — To include physical properties, electrical properties, environmental conditions under which equipment must be capable of operating, controls, and methods of operation
- Communication cable — To include insulation, color coding, physical properties, and electrical properties

Computer-based digital control systems will require technical specifications for items of equipment and services not normally found in conventional traffic control systems, among these may be the following:

- Map display — Specifications required for traffic parameters that are desired
- Cathode ray tube (CRT) or color graphics display — Specifications for parameters displayed and method of display
- Teleprinter — Specifications for parameters displayed and method of display
- Operator's console or other manual intervention device — Specifications for method of operation
- Computer software — Specifications for the control package, instruction set, assembly programs, utility programs, and diagnostic programs
- Television (TV) surveillance — Specifications for TV monitor and cameras
- Communications equipment — Specifications for digital data communication modems and interface devices
- Timing plans — Specifications describing requirements for the development and provision of intersection and system timing plans

11.5 DELIVERABLE SERVICES

With a continuing growth in the application of digital computers to traffic control, a need has developed to add to the specifications a general category which could be called deliverable services. This section of the specifications should define the responsibilities of the contractor to provide system design and engineering, system management, installation of computer hardware and software, complete system documentation, training of personnel, timing-plan development, timing-plan installation, startup assistance, and initial maintenance.

The following is a brief description of those items which can be classified as deliverable services:

Systems Management

Systems management includes responsibility for all the tasks related to the project in the following areas:

- Design
- Manufacture
- Procurement
- Assembly
- Testing
- Installation
- Initial operation
- Initial maintenance

The systems manager or contractor should be required to direct, coordinate, review, monitor and control the project to maintain a project schedule for the timely and adequate completion of the project.

Submission and frequent updating of a detailed project implementation schedule should be a requirement.

Documentation

System documentation is an absolute necessity for a successful system operation. It should not only be required, but it should be provided in sufficient detail to reflect as-built plans and to fully describe the methods of operation, maintenance, modification, and expansion of the system or any of its individual components. Where manufacturer-supplied documentation covers these requirements, it should be used in lieu of specially prepared material. Hardware documentation should include the following:

- General description — General description of all of the components comprising the system
- Theory of operation — Detailed description of the operation of the system, to include schematics, logic, data flow diagrams, etc.
- Normal operating procedure — Description of the procedure for the routine operations of the system
- Maintenance — Copies of manufacturers' recommended procedures and the checks necessary for preventive maintenance; provision of data necessary for isolation and repair of failures or malfunctions (corrective maintenance); and detailed maintenance instructions where failure to follow special procedures would result in damage to equipment or danger to operating or maintenance personnel
- Installation — Detailed description of physical and electrical properties of the system and other pertinent information necessary for the installation and use of the equipment
- Parts list — Listing and identification of various parts of system
- Schematic diagrams — Complete and accurate schematic diagrams to supplement text material
- Maps or drawings — Drawings of conduit layouts, cable diagrams, wiring lists, cabinet layouts, wiring

diagrams, and schematics of all elements of the communication system

Software documentation and rights are generally more difficult to specify and obtain. For many hardware elements, unique software provided in memory is considered proprietary. Such software, sometimes called firmware, provides all operational features specified and supports flexible operation through a wide array of user input-output options. In such cases, the user may never need access to those programs for modification, and thus not need detailed software documentation. However, in larger computer-based systems, the user may have need to modify or expand the system, thus requiring access to the software. In such cases, it is necessary to have access to *source* programs. Further, a full complement of executive, utility, and basic library programs for the computer system must be specified, along with the system programmer's and user's manuals. There are, generally speaking, the following three levels of software rights:

- Proprietary software — The purchaser has no rights to proprietary software other than that provided by license or use agreement.
- Semiproprietary software — The user (or purchaser) has no rights to semiproprietary software unless needed assistance is not available from the supplier
- Full rights — Rights to use, modify, and transfer software are conveyed and restricted only as defined by specific agreement

Control system specifications should specify the required level of purchaser rights so that all bidders can reflect these requirements in their proposal or bid.

With regard to the timing of when documentation is to be provided, the following suggestions are considered appropriate:

- Programmer's manuals and computer user's manuals should be available for agency staff use soon after the selection of a specific computer system with peripherals.
- Equipment manuals should be provided concurrent with the onsite delivery or storage of hardware elements, with such manuals obviously available for technician's study prior to any maintenance training.
- Cable routing details and wiring diagrams reflecting as-built conditions should be available after installation and prior to use of those components in order to facilitate maintenance.
- Application program flow charts, listings, and narrative descriptions, along with a draft system user's manual, should be available onsite prior to conducting operator training and prior to placing any intersection under the control of the system.
- The final payment for system installation should be withheld until acceptable final documentation is provided.
- Where a period of operational support is provided (see a following discussion), updates to final documentation should be required.

It is imperative that complete documentation be obtained. All submitted material should be closely studied and applied during the initial system implementation to assure not only that all needed documentation exists, but also that it is complete and clear to the operator.

Documentation becomes more valuable over time because, as the system ages, it experiences maintenance and modifications, and personnel changes occur. Therefore, the management and preservation of documentation that is provided should also be considered a necessary responsibility.

Training

Traffic control system training typically is provided in the principal areas of operation and maintenance. Further, such training may be structured to specifically address the needs of the individual levels of staff — management/supervisory staff, system operators, and maintenance technicians.

The purpose of training is twofold. First, and most obvious, training should provide those technical skills needed to effectively utilize and maintain all the features and components of the system. In this respect, the training specified and provided should reflect an appraisal of the actual needs of agency personnel.

If, for example, maintenance personnel are already routinely providing maintenance on microprocessor-based controller units, the training required could be limited to familiarization sessions on the actual unit provided. In contrast, an agency converting from old, pretimed hardware to microprocessor-based controller units should specify extensive training, perhaps even to include the operation and use of testing equipment.

A secondary purpose of training is to foster acceptance of the new system among agency personnel. It is well documented that a fear of the unknown can detract from full utilization of a new system. Thorough training, and perhaps even cross-training, can provide opportunities for involvement which break down those natural barriers to system acceptance.

Training may be provided at three distinct points in time:

- Preinstallation training
- After installation (before use)
- During operation

Preinstallation training offers an early opportunity to gain skills in a nonpressured environment on subjects such as the following:

- Equipment configuration
- System capabilities and features
- System operation
- Logistic support requirements
- Programming concepts
- Data base needs and preparation

As indicated, an actual hands-on experience with hardware may not be necessary in order for training at an early date to be meaningful. During the system-installation period, other opportunities for training are available. Here, maintenance personnel can be given detailed training in the operation of and in the preventive and corrective maintenance (trouble shooting) procedures for each equipment component. Actual hardware should be available during this time for hands-on training.

After system acceptance and during the period of extended operation, other opportunities for training may be directed toward refresher training for operations/maintenance personnel, or deal with the ever-present management problem of personnel turnover.

Regardless of when, or how much, system training is specified, system contractors/suppliers are anxious for the user to be knowledgeable and proficient in the use and care of the system. However, formal training is expensive — both to the contractor and to the user. Because of this, numerous users of successfully operating systems confirm the view that the *best training is gained by an active, aggressive involvement with the contractor during the system's installation, checkout, and initial operation.*

Startup Assistance

The period of initial system operation is typically a time of intense system activity. Maintenance problems associated with the full exercise of hardware, coupled with any remaining unfamiliarity with hardware, can be expected. Software bugs may surface, and the refinement of timing plans and data base is necessary. In addition, operator skills and day-to-day routine operational skills are developing. During this time, the successful operation of the system can be enhanced by having the continued support of the systems manager or contractor.

This continued assistance beyond system acceptance has been termed startup assistance and is considered by FHWA to be an eligible item for funding assistance. Specific tasks which may be accomplished as startup assistance include the following (*9*):

- Provide systems engineer to assist agency operators/engineers in adapting the system to reflect the needs of the local traffic environment
- Define and correct hardware and software deficiencies which can be discovered only through sustained operation
- Assist in maintaining, repairing, and replacing failed system components
- Provide on-the-job training as an extension of formal training provided earlier
- Prepare and provide updates for system documentation

Warranties/Guarantees

The period of time after system acceptance for which the contractor is to guarantee his work and materials should be specified. For hardware, a manufacturer may warrant his product for 6 months or more *from the date of delivery.* Problems arise when such items are stored or otherwise not used as part of the system until later in the project. To avoid problems of interpretation, the specification should clearly require the contractor to guarantee all hardware items for some time beyond final *system* acceptance. Further, any remaining equipment warranties by individual hardware manufacturers should be passed on to the agency.

Maintenance

Maintenance responsibility for hardware items installed as part of the system should be clearly specified. Common practice says that any item installed by the contractor is his responsibility until the system is accepted under the conditions of the contract. But beyond that date, and perhaps during a period of startup assistance, FHWA policy has clearly defined maintenance activities beyond system acceptance to be ineligible for Federal funding. However, some agencies have included a separate nonparticipating bid item for maintenance during an initial period of operation (possibly 1 year) in order to accomplish the following:

- Assure a source of maintenance during a critical time of system operation

- Determine maintenance costs to be expected at system completion
- Place responsibility for maintenance on the systems contractor, feeling that such responsibility might influence the choice of more reliable hardware and encourage quality construction of the system

Provision of spare parts and/or subsystems is also an important consideration. Even though Federal funds cannot be used for their purchase, because they are considered maintenance items, it is perhaps wise to include spare parts as nonparticipating bid items in the original contract. This is particularly appropriate when custom-made subsystems, such as modems, are required. Further, it may be desirable to include a requirement which permits the future purchase within some specified short time period of certain components at an established price.

System Acceptance Test

The testing of the installed control system should precede the acceptance of the system by the engineer. Testing is essential when a subsystem is to be installed by others. The methods for testing and documentation of the tests should be specified. In general, acceptance testing should consist of the following:

- Equipment checkout tests — Each major system component should be tested on an individual basis to verify its operation. This should include the diagnostic testing of each functional feature of items, such as controller units and detector electronics, and environmental testing of components and subsystems. Such testing can be done on a sampling basis, but full testing of each delivered item is recommended. The facilities for such testing may be provided by the systems manager or contractor, the agency, a state highway department, or an independent testing laboratory.
- System electrical tests — Tests to determine electrical continuity should be specified. These tests should be carried out for each conductor, including the spares.
- Computer software tests — The contractor should be required to test and demonstrate each feature of the control system software.
- System operations tests — The installed system should be tested to determine the total system's reliability and performance.

Testing individual components of the final system as they are delivered and/or installed is intended to detect problems early and correct them immediately. The alternative of waiting and simply testing the final system lets small problems compound to the point that they create serious problems affecting the total ability of the system to perform as specified. In either event, a final systems acceptance test is considered mandatory. A sample specification for such a test is shown in Figure 11.2 (*10*).

11.6 PROJECT MANAGEMENT

Project management is a technique that transforms a need into a reality in a controlled way. In everyday terms, project management could be considered putting it all together. Its main goal is to attain the overall system goals in the shortest time for the least cost. Project management thus implies getting the most out of the available resources. The following are some of the methods by which the most may be obtained from available resources:

- Provide visibility of the actions within the project
- Establish orderly procedures for attaining ultimate goals
- Centralize the responsibility and accountability

Whether the traffic control system is designed and implemented in-house by the responsible agency or by a systems firm or contractor, the principles of good project management should be followed.

Project management requires the management of a large number of different elements in the following dimensions:

- Time
- Space
- Financial terms

The different elements which are represented can be listed as follows (*1*):

- Diverse technologies
- Involvement of numerous agencies
- Diverse interfaces
- Scheduled interrelationships
- Cost considerations
- User support, including documentation and training

Project management also concerns itself with the management of many technologies such as the following:

- Traffic engineering
- Civil engineering
- Electrical engineering

2.8.3.4

System Acceptance Test

After installation and debugging of all central control equipment, local controllers, detectors, communications, and other system hardware and software elements, the system shall be required to satisfactorily complete a thirty (30) day period of acceptable operation. The intent of this System Acceptance Test is to demonstrate that the total system of hardware, software, materials and construction is properly installed; free from identified problems; complies with the specifications; and has exhibited the stable, reliable performance level required for the control of traffic. The System Acceptance Test shall fully and successfully demonstrate all system functions using live detector data and controlling all system-controlled intersections.

2.8.3.4.1

Action in Event of Hardware Failure

Failure in any hardware item during the test period, with the exception of expendable items such as bulbs and fuses, shall necessitate restarting the 30-day test period for its full 30-day duration for that item after its repair.

2.8.3.4.2

Action in Event of Software Failure

Any failure of system software, or discovery of a software deficiency which causes a system malfunction, or discovery of software operation which is not in compliance with the specifications, shall cause the 30-day test to be halted and repeated in its entirety for the software, after correction of the software problem. If no further software problems are discovered, and if no software problems are introduced as a result of correcting the initial deficiency, the Engineer may reduce the restarted 30-day test period for software to not less than 15 days. In no case shall the total test period be reduced under 30 days.

2.8.3.4.3

Uncertain Causes of Failures

In the event a problem is discovered for which it is uncertain whether the cause is hardware or software related, the 30-day test restart and repeat shall follow the procedure defined in 2.8.3.4.2 for software.

2.8.3.4.4

Persistent Intermittent Failures

No intermittent hardware, software, communication or control operation, or other malfunctions not related to a specific hardware or software malfunction shall be permitted to persist during the test period. If such problems are encountered, the test shall be suspended until the problem is corrected.

2.8.3.4.5

System Shutdown for Testing/Correction

While it is the intent that the system be fully operational during the entire System Acceptance Test, the possibility for system shutdown for purposes of testing and correcting identified deficiencies is acknowledged. During any period that the system operation is restricted or limited in any way as a result of testing, the 30-day System Acceptance Test shall be halted and shall not continue until a period of 72 to 168 hours of successful performance, as determined by the engineer, has proven that any corrections or modifications made are valid, the problem corrected, and no new system problem or deficiency created as a result of the change. Diagnostic testing which does not result in changes to system hardware or software shall result only in the loss of acceptable test time.

2.8.3.4.6

Maximum Downtime

Total system downtime in excess of 72 hours during the 30-day test period shall cause the System Acceptance Test to be restarted. System downtime is defined as a condition which, due to central control hardware, software, or communications equipment malfunctions, causes the system to operate in a standby mode, causes the central system to cease operation, or causes any subsystem to revert to its locally generated standby timing program.

2.8.3.4.7

Documentation Updating

All system documentation having errors, omissions, or changes which may have been detected or occurred as a result of system modifications or other reasons during the 30-day test period, shall be corrected and resubmitted before final system approval is granted.

2.8.3.4.8

Acceptable Performance

Final system acceptance shall not be granted until the level of performance for each hardware item and for system software as defined in this section and in all other sections of the specifications has been reached, and all other contractural elements (excluding Operational Support and Maintenance) have been met to the satisfaction of the engineer.

Figure 11.2. Sample Specification — System Acceptance

Source: Reference (*10*)

- System engineering
- Programming
- Field engineering
- Procurement
- Administration

Contract Administration

A critical element of system implementation and project management is the administration of the contract for construction. Such contract administration includes technical inspection, witnessing of acceptance tests, and other technically oriented tasks, along with administrative tasks such as processing payment requests, negotiation of change orders, and detailed recordkeeping in accordance with state and Federal requirements. From a workload viewpoint, a variable staff of personnel may be required over the life of the project. Also, it is important to ensure that required technical and administrative expertise is represented. Organizationally, contract administration duties are performed by, or under the direction of, a single project engineer (or project manager).

Scheduling

The construction phase can best be managed by the use of some method of project scheduling. The purpose of project scheduling is to set forth the tasks required to complete the project and to show their interdependency. Methods of project scheduling commonly used include the following:

- Project Evaluation and Review Technique (PERT)
- Critical Path Method (CPM)
- Bar charts

No matter what type of project scheduling is used by the systems manager during the project implementation phase, he should recognize that accountability for the end product must be clearly defined at all times during the implementation phase.

Project Evaluation and Review Technique (PERT). In Figure 11.3 is an example of a Project Evaluation Review Technique (PERT) chart extracted from the Chicago CBD Traffic Control System Report (*11*). Although this system was one of the first such systems implemented, the interdependency of the various subtasks can be realized from this illustration (e.g., subtask 1.9 is dependent on the completion of subtasks 1.2, 1.4, and 1.7). The PERT chart provides a guideline for the systems manager to set forth the interdependency of the tasks and subtasks and to ensure the timely, and adequate completion of the project. Unforeseen delays in the procurement and installation of equipment will necessitate a revision of the PERT chart to alter the time frame for the completion of subtasks, while still maintaining a reasonable overall project schedule.

In Table 11.1 are shown the results of the PERT analysis for the Chicago CBD traffic control system (*11*). From this Table, it can be seen that the estimated total time (TT) to complete the project is 35 months. Also shown are the following:

- Earliest time of completion (ET)
- Latest time of completion (LT)
- Slack time (ST)
- Critical subtasks (CS)

The earliest time of completion (ET) of a subtask is that time at which it will be completed if the preceding subtasks are completed as early as possible. The latest time (LT) of completion of a subtask is that time at which it can be completed without delaying the completion of the total project. Slack time (ST) is the difference between the latest time (LT) and the earliest time (ET). Critical subtasks are those having zero slack time.

Though this version of a PERT chart identifies only the subtasks that must be completed on time in order for the project to be completed on time, it is particularly useful since it can be employed to review the progress of the entire project. However, the PERT chart does not take into account the *cost* of performing the subtasks, which is usually dependent on the amount of time scheduled for their completion. In most cases, though, it should be recognized that, if necessary, a subtask could be completed in a shorter amount of time if a higher cost were allotted.

Critical Path Method (CPM). The critical path method (CPM) has proved to be a very successful method for planning, organizing, and controlling projects. The initial phase of this management tool outlines the project graphically in the form of a network diagram. This graphic representation, as presented in Figure 11.4, illustrates the required operational sequence and also indicates which operations are concurrent and which must be completed before others can be initiated. The CPM operations are referred to as activities.

In Figure 11.4, which is an example of the application of CPM to the installation of a traffic control system, the activities necessary to complete the project are denoted by a line with an arrowhead. The circled numbers represent events which mark the beginning or completion of an activity. Dashed lines represent dummy activities

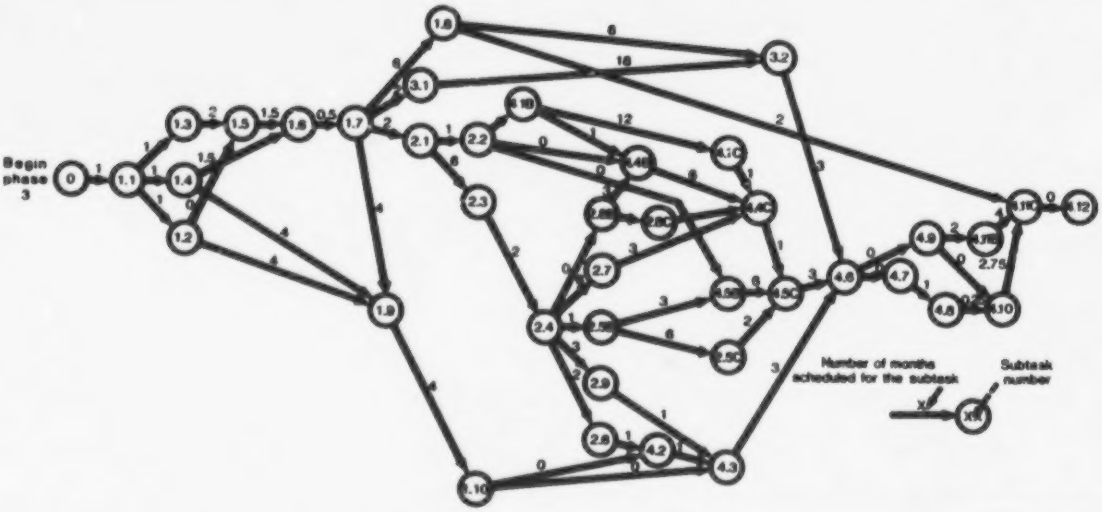


Figure 11.3. Initial implementation PERT chart, Chicago (Illinois) central business district (CBD) traffic control system

Source: Reference (*11*)

which do not require any time but must be completed before another event can occur. The number below the activity represents the amount of time required to complete the activity. The critical path represents the project duration. In the example, the critical path is represented by the activities associated with events 1-11-15-19-23-27-29-31.

In the example, if activity 7-21 required a time of 10 instead of 8, then the critical path would become 7-21-23-27-29-31, because this sequence of activities would require a longer time. In this case, the receipt of the mast arm poles would establish the critical path because they must be received before they can be set in place.

The network diagram should be updated periodically to account for factors which would delay the project completion. These factors include longer delivery dates, delays caused by weather, change orders, etc.

Bar Charts. The use of bar charts as a method of project scheduling is shown in Figure 11.5 (*12*). This bar chart for the Greensboro, North Carolina, Traffic Control System depicts the time relationship for completion of the various project tasks. Starting and ending dates and durations are shown for the various tasks. Also shown are milestones (the start or completion of a task). The interdependency of tasks is indicated by a dashed line (e.g., M6 indicates the interdependency of acceptance tests for controller assemblies and the installation of communications lines).

11.7 IMPLEMENTATION PITFALLS

The previous discussions of system design and implementation have focused on those positive steps that lead to successful system acceptance. O'Malley summarizes these as follows (*3*):

- Commitment, on the part of all parties, to work through difficulties with an attitude of cooperation
- Contract management, which balances firm control and fairness through a single person in charge
- Systems engineering expertise, with the experience and capability to integrate hardware and software
- System and component acceptance testing, which assures compliance with specifications
- Documentation and training, for all elements of the system, presented in a timely fashion to meet the needs of different levels of operations and maintenance personnel

In the following discussion, the reverse perspective is presented. Basically gleaned from the results of discussions and contact with system users, these pitfalls are presented to assist in avoiding mistakes made in the past. In each case, the generalized pitfall is presented, and then suggestions for avoidance are described. They are presented in no specific order of importance.

Table 11.1. Initial PERT analysis, Chicago (Illinois) CBD traffic control system

Number	Subtask Designation	Completion Dates	
		Earliest (Months after Start of Project)	Latest (Months after Start of Project)
*1.1	Organization of coordinating committee	1.0	1.0
1.2	Selection of control center site	2.0	4.0
*1.3	Preparation of financial plan and budgets	2.0	2.0
1.4	Selection of city project engineer	2.0	4.0
*1.5	Advertising for bids	4.0	4.0
*1.6	Review of bids	5.5	5.5
*1.7	Awarding of contract(s)	6.0	6.0
1.8	Development of control management standard operating procedures	12.0	21.0
1.9	Preparation of control site design	10.0	22.0
1.10	Preparation of control site	14.0	26.0
*2.1	Preparation of detailed PERT chart by hardware contractor	8.0	8.0
*2.2	Development of schedules for installation of communication lines, controllers, and detectors	9.0	9.0
2.3	Development of prototype hardware system	14.0	15.0
2.4	Prototype hardware acceptance testing	16.0	17.0
2.5b	Beginning of detector manufacturing	17.0	25.0
2.5c	Completion of detector manufacturing	23.0	26.0
2.6	Standby master controller manufacturing	18.0	25.0
2.7	Communication equipment manufacturing	22.0	23.0
2.8b	Beginning of intersection controller manufacturing	16.0	17.0
2.8c	Completion of intersection controller manufacturing	22.0	23.0
2.9	Computer and peripheral equipment manufacturing	9.0	16.0
3.1	Preparation of detailed PERT chart/work plan by software contractor	8.0	9.0
3.2	Software development	26.0	27.0
*4.1b	Beginning of installation of communication lines by city crews	13.0	13.0
*4.1c	Completion of installation of communication lines by city crews	25.0	25.0
4.2	Installation of standby master controller	19.0	26.0
4.3	Installation of computer and peripheral equipment	20.0	27.0
4.4b	Beginning of installation of controllers	19.0	20.0
*4.4c	Completion of installation of controllers	26.0	26.0
4.5b	Beginning of installation of detectors	20.0	21.0
*4.5c	Completion of installation of detectors	27.0	27.0
*4.6	Operating testing	30.0	30.0
4.7	System on line	30.0	32.75
4.8	Beginning of automatic surveillance and data collection	31.0	33.75
*4.9	Beginning of acquisition of operational experience	30.0	30.0
4.10	Beginning of data analysis	31.25	34.0
*4.11b	Beginning of training of city personnel	32.0	32.0
*4.11c	Completion of training of city personnel	36.0	36.0
*4.12	Beginning of computer control operations	36.0	36.0

*Critical subtask

Source: Reference (*11*); adapted

Inexperienced Contractors

The installation of traffic control systems is perhaps viewed by some contractors as just another highway job. Failure to recognize the systems integration needs of such a project, however, generally spells disaster. In some cases, traffic control projects are embodied as a small portion of a large general construction project. Doing so virtually assures that a subcontractor will be used for this critical element. This raises the question of what control is exercised on subcontractor selection, and what control is applied on specific selection of hardware. In some early cases, contractors have apparently bought projects, underbidding and losing money in order to gain experience in the field.

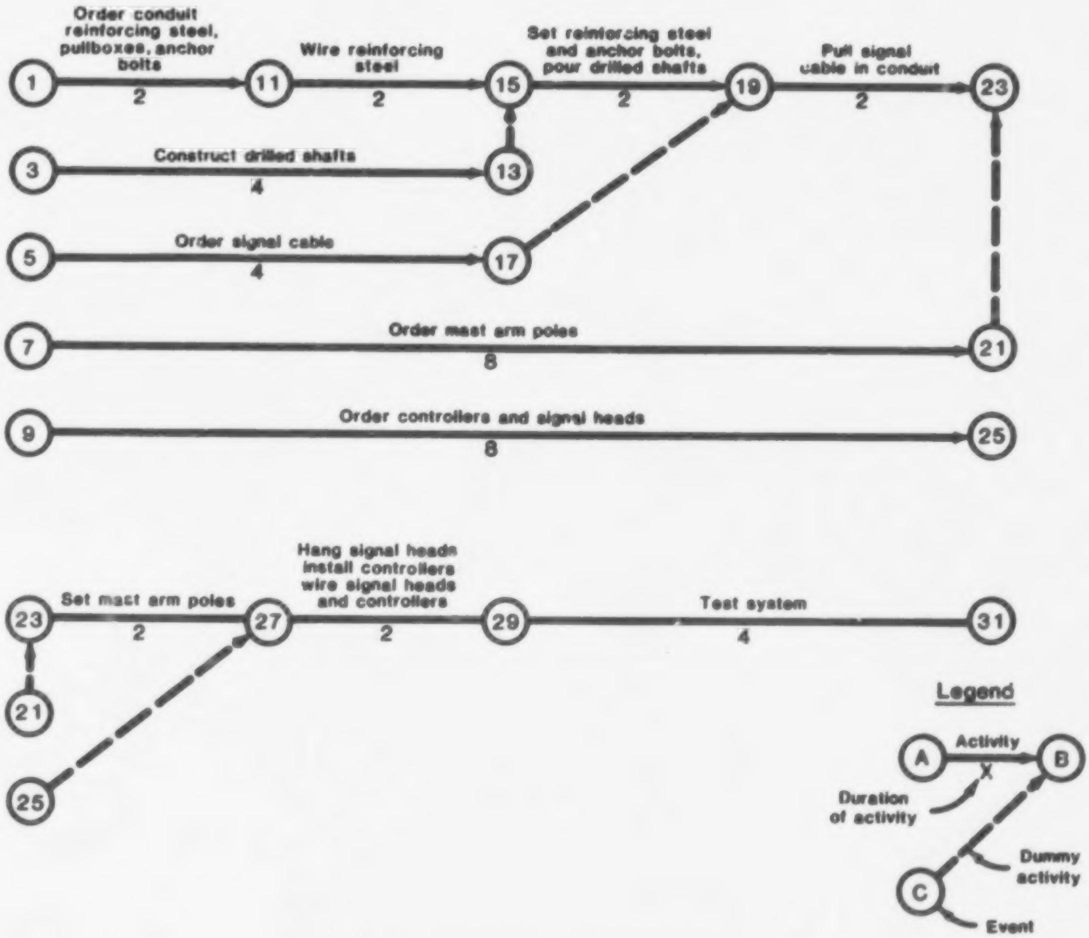

Order conduit reinforcing steel, pullboxes, anchor bolts
2
Wire reinforcing steel
2
Set reinforcing steel and anchor bolts, pour drilled shafts
2
Pull signal cable in conduit
2
Construct drilled shafts
4
Order signal cable
4
Order mast arm poles
8
Order controllers and signal heads
8
1
11
15
19
23
3
13
5
17
7
21
9
25
Set mast arm poles
2
Hang signal heads install controllers wire signal heads and controllers
2
Test system
4
23
27
29
31
21
25
Legend
A
Activity
B
X
Duration of activity
Dummy activity
C
Event

Figure 11.4. Example of CPM network diagram

This pitfall is perhaps best avoided by (1) separating control system elements from large projects where they may be lost, and (2) by requiring contractor prequalification on the basis of demonstrated experience.

Construction Management

Construction management entails project engineer inspection of day-to-day construction activities, witnessing of acceptance tests, and other technically oriented duties. Further, it involves recordkeeping, in accordance with state and Federal requirements, of items such as review and approval of shop drawings, identification of need for change orders (including negotiation with the contractor on the change and compensation), and obtaining necessary reviews and approvals prior to authorization.

Construction management requires both a high degree of technical knowledge and experience in managing contracts. While typical state project engineer and inspection personnel are generally proficient in project management for typical highway construction jobs, they may lack electronics and control system technical expertise. In contrast, city traffic engineer and signal maintenance personnel may have the technical expertise but have little experience in project administration. Project engineers assigned from either experience background may tend to retreat to the familiar, with an attendant negative impact on effective project management.

Some projects have experienced problems with the inspection of system construction, ranging from token ineffective inspection to unyielding insistence on a strict

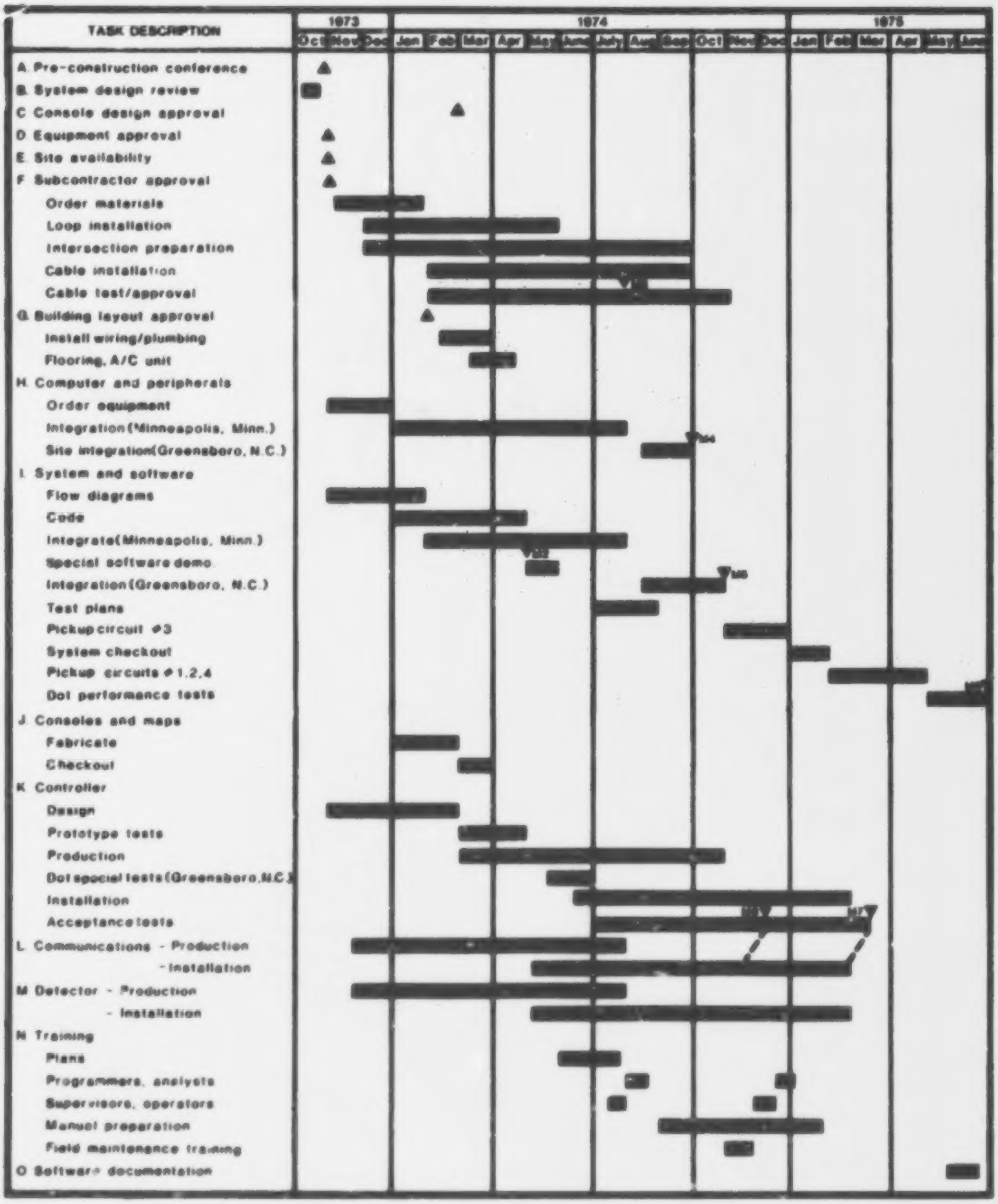


Figure 11.5. Greensboro (North Carolina) traffic control project milestone schedule

Source: Reference (*12*)

interpretation of specifications. Most common is the failure to anticipate the contractor's schedule and pace of construction and thus not match it with qualified inspectors. In some cases, totally inexperienced personnel have been assigned. On other projects, inadequate numbers of inspectors have been assigned. The best technical inspectors for any system are those individuals who will be operating and maintaining the system once it is completed. If at all possible, they should be assigned inspection duties and have their other routine activities rescheduled to minimize conflicts.

These needs should be carefully considered in planning for the project. Desirably, a team approach will be taken, such as with a project engineer having access to technically qualified personnel for specialized inspection tasks as necessary.

The channels of higher authority should also be identified and a working relationship established. A formal or informal project committee may be useful so that everyone involved can periodically meet, be apprised of the broad picture, review progress, and address potential problems before they become critical.

Timing Coordination during Construction

Disruptions to traffic during construction are to be expected. Most designers remember to specify such things as how many lanes can be closed simultaneously for detector installation, or what hours are permitted for construction to avoid peak-hour interference. But other questions arise, such as what to do about construction impacts downtown during a Christmas shopping rush. Or, of more frequent concern, problems arise about what to do about signal coordination during construction, such as how many signals can operate noninterconnected (or uncoordinated) and for how long. In one case, interconnect conduit was to be reused. Old cables were removed and extensive delays were encountered in the installation of new cables and interconnection, all with predictable results on efficiency of flow and negative public relations.

To avoid such pitfalls, plans for traffic handling during construction are necessary, even to the point of preparing or requiring the contractor to prepare a formal traffic-handling plan. Perhaps a redundant backup system would be needed, or time-based coordination could be used.

Data Base Development

Computer-based traffic control systems require an extensive data base on which to operate. Frequent problems have been encountered in that no specific assignment of responsibility was fixed for necessary traffic surveys and development, coding, input, and debugging of data base information. Without clear definition, the user might be responsible for more than he realizes. Users should be actively involved in data base preparation, but waiting until the last minute to find out what the requirements are is again inviting disaster.

As a minimum, users should be actively involved, but perhaps they should fix the final responsibility on the contractor. This is also an area where training by the contractor is advisable.

Insufficient Staff for Operations and Maintenance

Overselling the capabilities of traffic control systems as alternatives to staff is a mistake. Systems must be maintained and actively managed in order to provide effective service. Although new hardware may indeed eliminate unreliable, high-maintenance equipment that has exceeded its useful life, perhaps even more sophisticated maintenance may then be required. In addition, equipment with greatly expanded capabilities may actually require more operations staff to realize its full potential.

The timing of staff additions is also critical. For example, system operators need to be employed and available to receive training provided by the contractor.

Utility Coordination

The installation of underground conduits and/or overhead cables may mean that conflicts with other public utilities will result. Regardless of how thorough the attempts in the design process are to locate and document existing utilities, when construction begins, some will be found in unexpected locations.

A good way to avoid serious problems in the coordination of utilities is to do a good job of documenting existing conditions, while also accepting the fact that unforeseen situations will arise. Then, during the design process, an attempt is needed to visualize the most likely problems and to preplan a response. For example, if planning calls for reusing existing conduit, a likely condition might be that the old cable cannot be removed because of conduit collapse. Therefore, the conduit cannot be reused. The preplanned response might be to ensure the inclusion of a bid item for conduit replacement which would adequately compensate the contractor for his attempts to reuse an existing conduit followed by its replacement. In this way, expensive change orders and delays are avoided.

Planned Use of Untested Facilities or Techniques

Problems have been experienced in two different ways with the planned use of untested facilities or techniques. First, from a construction viewpoint, one agency planned to use existing telephone company underground ducts for interconnect cables. Routing and design was based on available mapping and duct-use records of the company. No funds were allocated during the design process to rod the ducts and verify open paths — a task that was placed on the contractor. During cable installation, since a number of blocked paths were found, duct replacement was not possible during the available timeframe. Therefore, alternate paths with inefficient routing and resulting contractor change orders were necessary.

Secondly, with respect to hardware and applications software, pioneers should expect a measure of unexpected problems. Being the first to use a product, software, or technique that attempts to advance the state of the art poses risks.

Alienation of Maintenance Staff

The acceptance of new traffic control systems by all levels of an operating staff is very important to successful system operation. It is fostered by active involvement — not only during installation but also during both the design and predesign activities.

Maintenance staff in particular may feel threatened by a new system, particularly if a large amount of unfamiliar new hardware is provided. They may have unexpressed concerns about the system's impact on their job security, doubts about their skills to maintain it, and feelings that the engineer's new toy just means a more difficult job for them. Such fears may be minimized by the following:

- Early involvement of maintenance (and other) staff in system feasibility studies and system selection to ensure proper consideration of reliability and maintainability issues
- Assurance of early, thorough training tailored to staff needs
- Opportunities for involvement through construction inspection

This discussion of pitfalls is by no means complete. Traffic control systems, because they must be installed in full public view and because of their daily impact on motorists, offer highly visible opportunities for criticism when things go wrong. Thoroughness in design and construction planning is a necessity, along with strict attention to details during construction. The hardware problems can be identified and corrected — , but the people problems require constant attention.

REFERENCES

1. Cleary, Edward F. "Characteristics of Systems Management." *Traffic Engineering*, Vol. 43, No. 1, October 1972, pp. 26-30.
2. Kittudes, Christopher P. "Construction Management: State of the Art in 1974." *Professional Engineer*, Vol. 44, No. 6, June 1974, pp. 22-26.
3. Klatt, Richard T., and Roy L. Wilshire. "Buying a Signal System: A Two-Step Procedure." *Traffic Engineering*, April 1974, pp. 14-15.
4. O'Malley, Dennis M., and Steven M. Pardee. "Albany's Computerized Traffic Control System: A Credit to Cooperation." *Computer Control Systems Application Group Newsletter* (Institute of Transportation Engineers), Vol. 6, No. 3, October 1983.
5. Meier, Hans W. *Construction Specifications Handbook*. Prentice-Hall, Inc., 1975.
6. Kell, James H., and Iris J. Fullerton. *Manual of Traffic Signal Design*. Institute of Transportation Engineers. Prentice-Hall, Inc., 1982.
7. *Standard Forms of Agreement*. Engineers' Joint Contract Documents Committee, National Society of Professional Engineers, Washington, D.C., November 1983.
8. "Installation of Highway Traffic Signals." Item 632, *Standard Specifications for Construction of Highways, Streets and Bridges*. Texas State Department of Highways and Public Transportation, September 1, 1982.
9. PRC Voorhees, Division of PRC Engineering. *Computer Controlled Traffic Systems*. Implementation Package, FHWA-IP-82-21, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. December 1982.
10. Central Business District Traffic Control System (CBDTCS). *System Specification*. Contract Number 79-200, City of Dallas, Texas, Department of Street and Sanitation Services, 1979.
11. Schlaefli, J. L.; D. P. Masher; D. W. Ross; J. O. Williams; and H. M. Zeidler. *Chicago CBD Traffic Control System, Volume I: Systems Analysis and Design*. Stanford Research Institute, Menlo, California, October 1971.
12. *A Traffic Control and Surveillance System for Greensboro, North Carolina*. Honeywell, Inc., Hopkins, Minnesota, October 1973.

12. SYSTEM MANAGEMENT

CONTENTS

Section *Page*

12.1 INTRODUCTION 12.3

12.2 A SYSTEM MANAGEMENT TEAM CONCEPT 12.3

12.3 OPERATION OF TRAFFIC CONTROL SYSTEMS 12.4
- **A Real-World Environment** 12.4
- **Control Periods** 12.4
- **Typical Operational Tasks** 12.5
  - *General System Operation* 12.5
  - *System Monitoring/Intervention* 12.5
  - *Data Collection and Analysis* 12.5
  - *System Modification and Updates* 12.8
    - *Updating of System Timing* 12.8
    - *Incorporation of Software Updates* 12.10
    - *Addition of New Control Features* 12.10
    - *Additions and Deletions of Signal Hardware* 12.11

12.4 STAFF REQUIREMENTS AND ORGANIZATION 12.11
- **Increased Opportunity for Interaction** 12.11
- **Staffing Examples** 12.11
- **Factors to Consider in Staffing** 12.11
- **Organization** 12.13

12.5 MAINTENANCE OF TRAFFIC CONTROL SYSTEMS 12.13
- **Types of Maintenance** 12.14
  - *Functional Maintenance* 12.14
  - *Hardware Maintenance* 12.14
    - *Field Equipment* 12.14
    - *System Masters* 12.15
  - *Software Maintenance* 12.16
- **Results of Inadequate Maintenance** 12.16
- **Staffing for Maintenance** 12.17
  - *Maintenance Skills Required* 12.17
  - *Assessment of Present Capability* 12.17
  - *Workload Impact* 12.17

12.6 EVALUATION OF TRAFFIC CONTROL SYSTEMS 12.18
- **Need for Performance Evaluation** 12.18
- **Evaluation Techniques** 12.18
  - *Before-and-After Measurements* 12.18
  - *Simulation Analysis* 12.19
- **Validity of Measurements** 12.19

361

Section *Page*

Threats to Internal Validity 12.19
Threats to External Validity 12.19
Sampling Considerations 12.20
Categories of Data Required 12.20
Descriptions of Improvements 12.20
Descriptions of Test Conditions 12.20
Descriptions of Measures of Effectiveness (MOE'S) 12.20

REFERENCES 12.22

12. SYSTEM MANAGEMENT

12.1 INTRODUCTION

When managed properly, traffic control systems (TCS's) can provide a tool to facilitate the optimum utilization of available street and intersection capacity. Capacity is a measure of the ability of the street and intersection geometry of the system to accommodate the movement of vehicles. No matter how elaborate or sophisticated a TCS might be, it cannot create capacity. For this reason, it should never be viewed as a total panacea for the solution of transportation problems. The TCS has, however, a very important role in Transportation Systems Management (TSM) activities. Almost all of the actions planned as TSM measures will impact or depend on the efficient and effective use of traffic control systems.

Flexibility is the keyword which best characterizes the operational attributes of state-of-the-art traffic control systems. Because the system masters utilize digital computer technology, these systems have effectively removed the formerly experienced hardware constraints to efficient operation, and have placed the burden of operational efficiency on the traffic engineer's ability to utilize the system to its full capabilities.

In order to reap any of the benefits of this flexibility, a TCS must be thought of as more than just a combination of hardware and software. The organizational structure and the personnel that comprise the operating entity must also be part and parcel of the system. If the TCS is to be made to realize its potential, not only must there be technical skills to match the equipment, but advanced management skills must be available to ensure that the system performs efficiently and effectively. The flexibility and real-time evaluation capabilities of today's systems demand operational and managerial supervision, and those traffic control systems, which are presently successful have proved that such attention pays off.

More and more, the agencies responsible for TCS management have discovered that an install-and-operate, or a set-it-and-forget-it policy is not sufficient. The potential of the system will never be realized unless these attitudes are replaced by a policy of install, operate, and *update*.

Managing traffic control systems requires consideration of three basic functional responsibilities:

- Operation
- Maintenance
- Evaluation

Each of these categories is explored in the balance of this chapter.

12.2 A SYSTEM MANAGEMENT TEAM CONCEPT

From an organizational point of view, TCS's, regardless of their level of sophistication, need to be integrated into a functioning traffic engineering department or its equivalent. Moreover, individual personnel assigned to tasks occupying one, or more, of the previously listed system management functional responsibilities listed above must be organized in a team effort. As shown in Figure 12.1, the three functional responsibilities for effective system management are interdependent, and they share the following relationships:

- System operation is not possible without proper system maintenance. Likewise, effective and efficient operation will never be realized without the evaluation element.
- System maintenance cannot be properly carried out unless a close working relationship with operational personnel is sustained. Information concerning the nature and extent of control system problems originates from the monitoring element of system operation.
- System evaluation depends upon both system operation and maintenance. For effective evaluation of any given control plan, the system must operate as error-free as possible, and with an absolute minimum of hardware failures. Operation during evaluation periods, thus, must be monitored closely by operations personnel.

Considering the above interrelationships, it is the responsibility of the managing entity to organize personnel into a cohesive unit in which needed information flows between work segments. The resulting management team concept will help to ensure that the TCS lives up to its expectations and produces the greatest benefits for the motoring public.

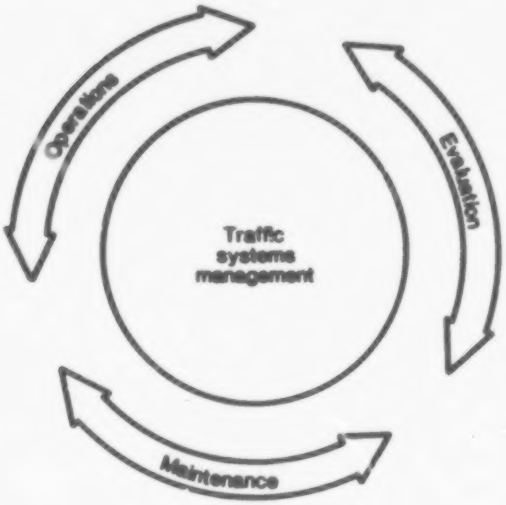


Figure 12.1 System management team concept

12.3 OPERATION OF TRAFFIC CONTROL SYSTEMS

Successful control operation is the essence of good management of the traffic control system. This section deals with practical aspects of operation, typical work tasks, and staffing requirements necessary for good system operation.

A Real-World Environment

Traffic control systems must function in the most demanding of all physical environments. Some system hardware is subject to highly variable extremes in weather, temperature, electrical noise and disturbances, as well as possible physical damage from vandals, out-of-control vehicles, etc. Yet, the system is expected to provide a highly reliable operation on a continuous basis, 24-hr each day of the year. There literally is no such thing as a safe or convenient break in system service.

Not only is the system's physical environment of a critical nature — its operational environment is even more demanding. Its daily operation is in public view where it directly affects each user. Because of this, considerable effort is justified in monitoring the system's performance to locate equipment malfunction and to effect timely repair. Likewise, modifications in system performance must be made to accommodate changes in traffic flows for the safety and convenience of motorists and for public acceptance of the system.

Once a TCS is placed in operation, it is difficult, from a practical viewpoint, to interrupt its service arbitrarily. While degradation to backup or fail-safe operation may be necessary on an emergency basis, such operation must not be used for an extended period of time. This situation emphasizes the need for highly reliable and well-maintained equipment, and illustrates a basic principle which influences virtually all operational decisions. The system must *work*; it must *work well*; and it *must work well* virtually *all the time*, if the public is to be served adequately.

Control Periods

In control systems of various types, different approaches are employed with regard to periods of operation. For example, a freeway control and surveillance system may be utilized in the control mode (for ramp metering) only during periods of congestion. As a result, the control may be limited to peak periods and may be further restricted to control of the peak direction only. Even some traffic signal control systems are presently being operated only during normal (predictably recurring) peak periods or during daytime hours, and then control reverts to some type of backup system for signal operation during off-peak or evening hours.

In the past, the diversion of computer time to applications other than system control was a legitimate factor in decisions to limit system supervision to certain hours. The desire to do program development, testing and debugging, and the need to perform statistical analyses of accident data, signal inventories, signal maintenance records, or nontraffic-related applications were among the various reasons given for interrupting the traffic control function. Many state-of-the-art systems must be taken offline for short periods for data base modifications, such as updating and rescheduling of signal timing plans, and subsystem reconfiguration.

Traffic control systems, to be truly effective, must be dedicated to continuous, real-time traffic control under the supervision of qualified traffic control personnel. Traffic engineering support programs should be accommodated only if they can be performed on a time-sharing or otherwise nonconflicting basis. The emergence of low-cost, high-capacity, personal-type computers over the past few years has provided a very practical alternative to the use of the system master computer for purposes other than its primary function, which is to control traffic.

Typical Operational Tasks

Effective control system operation includes a number of tasks which are discussed in the material which follows.

General System Operation. The day-to-day operation of the control system requires a number of basic regimented tasks and procedures which should be followed to assure continuity of operation, and to procure and retain archival data. Some suggested procedures and tasks are as follows:

- Maintain a daily control log which covers the entire control period. The log form should include a checklist of items and tasks, so that each shift operator is reminded of his or her responsibilities concerning (hardware/software-oriented) duty routines necessary for proper system operation. Entries in the log concerning system functions or component failures serve both as a written record of events per shift, and provide continuity in operation from one shift to the next. An example of a daily control log form is shown in Figure 12.2.
- Maintain a written ledger of timing-plan modifications showing date and time implemented, requestor, type of change (temporary or data base implemented), and reason for modification.
- Retain tape copy of daily summary reports (volumes, occupancies, failures, etc.) indefinitely for historical reference purposes.
- Retain hard copy of all failures, preemption periods, the sequential system operation record, etc. for at least a year. The daily report, usually generated at midnight in most system operation, typically contains this data.
- Back up complete system data base on tape, at least, on a monthly basis, i.e. (current minus 1 month, current minus 2 months). Then produce, and retain indefinitely, an archival tape of the system data base every 3 months.

Documentation is one of the most important aspects of the operation tasks. Incomplete, incorrect, or nonexistent documentation is usually reflected in the control system's performance. Careful documentation control and distribution to management team personnel provides an essential element for successful system operation. Every change in software, in operational control parameters, or in hardware components, no matter how trivial it may seem, should be documented; and *all copies* of the documentation should be updated. Any team member who makes a change, whether he or she is a technician, programmer, engineer or systems manager, should document it.

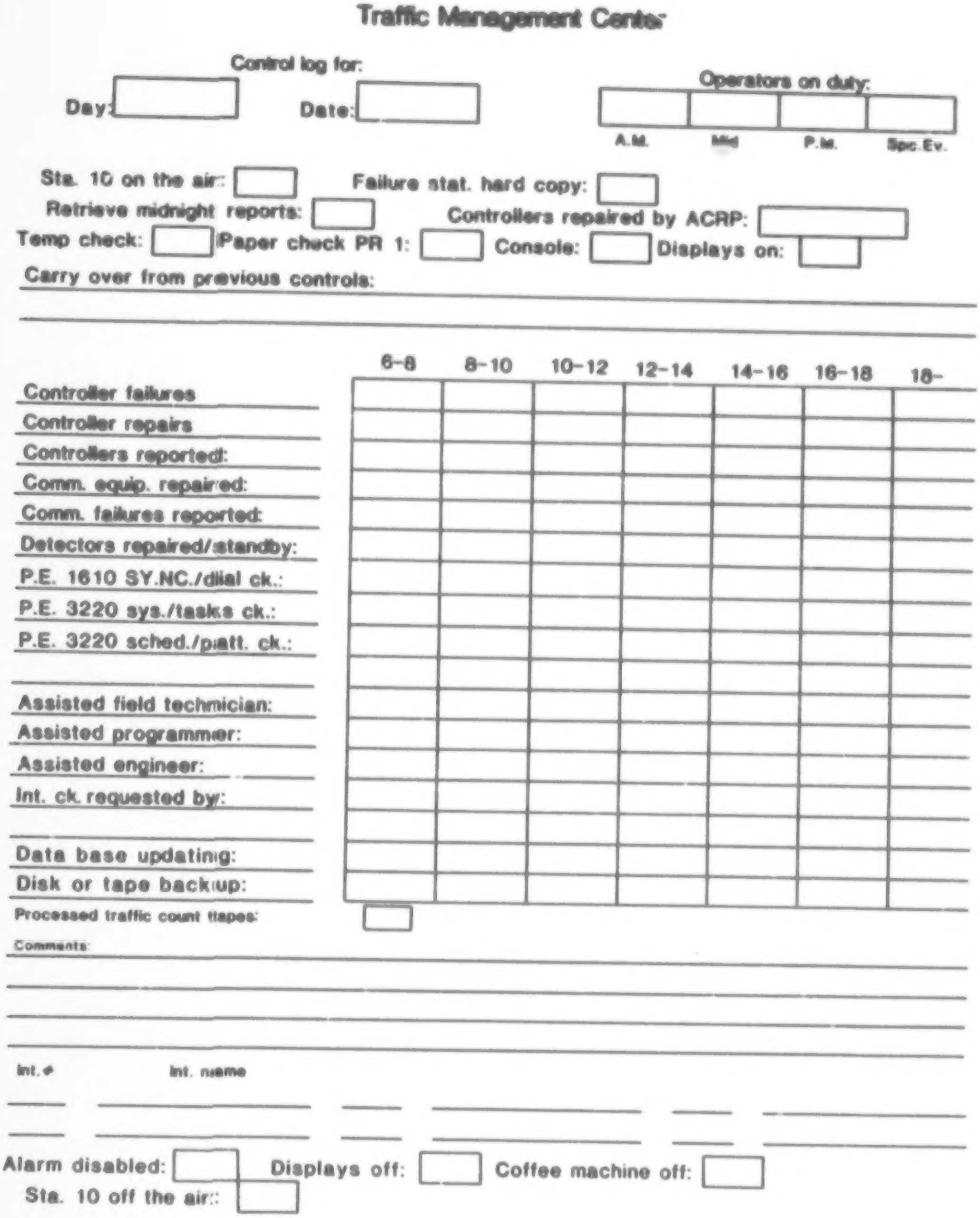
System Monitoring/Intervention. Most TCS's have the capability of virtually unattended operation. Predetermined schedules for time-of-day, or traffic-responsive implementation of timing plans (some possibly including section or subsystem reconfigurations), are carried out automatically. In normal operation, the time-of-day or processed traffic flow data are used to determine when the implementation of a group of specific timing plans for the system should occur. The system status monitoring element then verifies proper execution of the control patterns on the street. This closed control loop is graphically shown in Figure 12.3.

As shown in Figure 12.3, the normal automatic implementation of system configuration and timing can be modified through manual override by an operator. System status display, map display, or graphics display can also be changed from the control panel by an operator, but this action cannot be termed intervention, because system control functions are not interrupted.

Manual intervention typically occurs in response to congestion or maintenance problems and may be necessary to accomplish the following:

- Remove a failed controller unit or other component from system control in response to an alarm, and then dispatch maintenance personnel for repair
- Return repaired controller units or other components to system control
- Implement an emergency configuration and/or timing strategy
- Temporarily discontinue or restore system supervision at individual intersections in response to noted street congestion problems
- Change individual intersection timing parameters on a temporary basis

Data Collection and Analysis. In TCS's without surveillance capabilities, the traffic engineer must rely totally upon manually gathered field data and field observations of system operation to determine the effectiveness of implemented on control strategies. Analysis of the data and of observed field conditions provides the basis for modification of system timing and plan scheduling. One of the more tangible advantages of computer-supervised, surveillance-type signal systems is their ability to automatically gather significant amounts of various types of traffic data and to tabulate and analyze them in the course of normal operation. The data thus tabulated and analyzed produce measures of effectiveness (MOE's) for the system. Examples of data used to generate MOE's are volume, average speed, occupancy, queue lengths, delay, number of stops, and travel time.



Traffic Management Center

Control log for:

Day: ☐ Date: ☐

Operators on duty:

A.M.	Mid	P.M.	Spc.Ev.

Sta. 10 on the air: ☐ Failure stat. hard copy: ☐

Retrieve midnight reports: ☐ Controllers repaired by ACRP: ☐

Temp check: ☐ Paper check PR 1: ☐ Console: ☐ Displays on: ☐

Carry over from previous controls:

	6-8	8-10	10-12	12-14	14-16	16-18	18-
Controller failures							
Controller repairs							
Controllers reported:							
Comm. equip. repaired:							
Comm. failures reported:							
Detectors repaired/standby:							
P.E. 1610 SY.NC./dial ck.:							
P.E. 3220 sys./tasks ck.:							
P.E. 3220 sched./patt. ck.:							
Assisted field technician:							
Assisted programmer:							
Assisted engineer:							
Int. ck. requested by:							
Data base updating:							
Disk or tape backup:							

Processed traffic count tapes: ☐

Comments:

Int.# Int. name

Alarm disabled: ☐ Displays off: ☐ Coffee machine off: ☐

Sta. 10 off the air: ☐

Figure 12.2. Typical daily control center log form

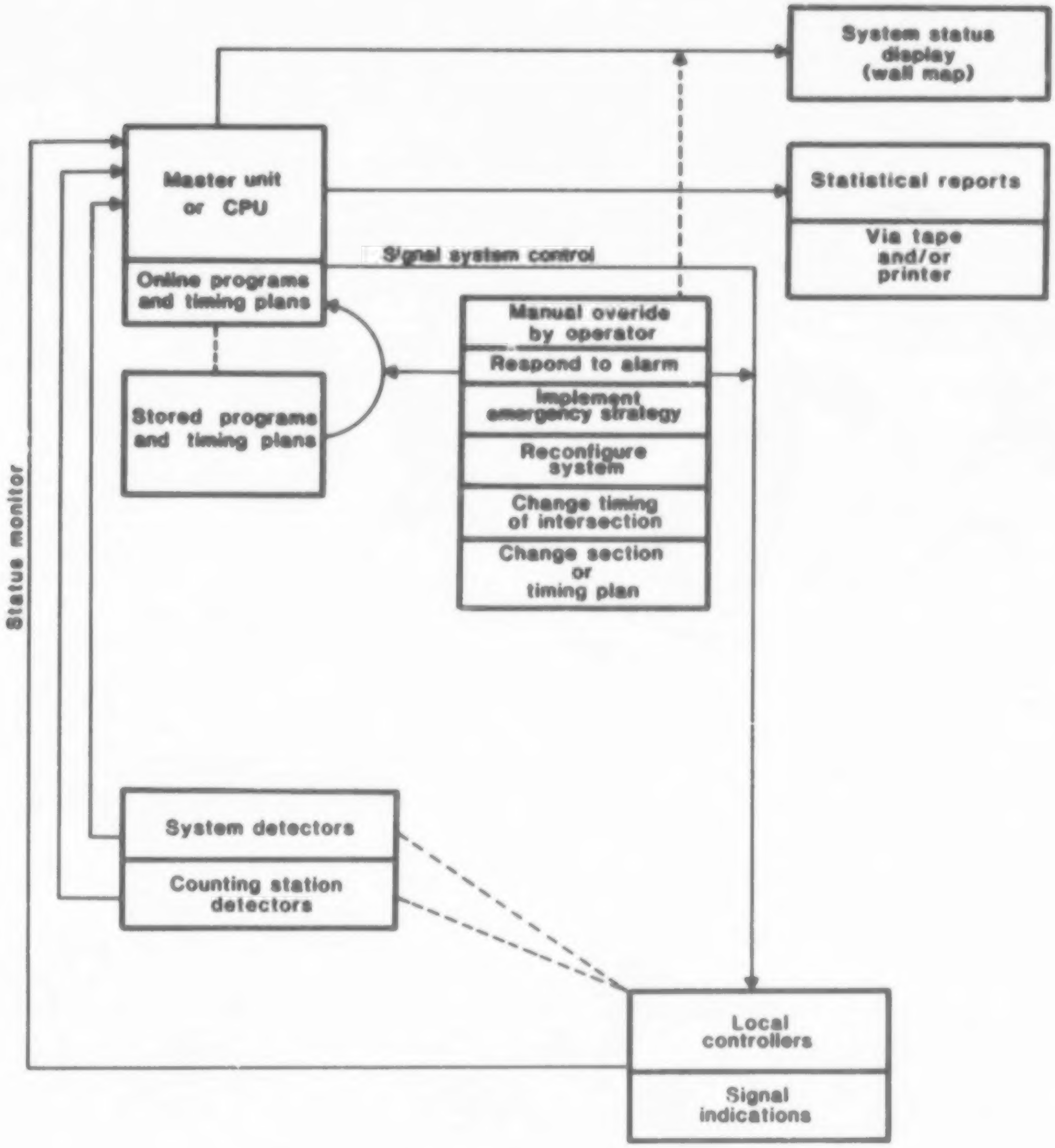

System status display (wall map)
Master unit or CPU
Statistical reports
Via tape and/or printer
Signal system control
Online programs and timing plans
Manual overide by operator
Respond to alarm
Implement emergency strategy
Reconfigure system
Change timing of intersection
Change section or timing plan
Stored programs and timing plans
Status monitor
System detectors
Counting station detectors
Local controllers
Signal indications

Figure 12.3. Typical system control and operations architects

For ease in analysis of system operation, MOE's must be assembled in usable form. If personnel are to utilize the data effectively to improve system-control operation, they must be able not only to easily understand what the respective printouts and graphics represent, but also how they fit in to the elements of system control. MOE's usually derived on a per-link basis should be converted into an aggregate matrix for respective control subsystems or sections, as well as for overall system coverage.

367

Since no two systems are identical, it cannot be overstated that each system's software must be tailored to produce appropriate text and graphic printouts of MOE's.

Some suggested formats for hard copies of MOE's and their usage are as follows:

- A graphic presentation of system or section aggregate MOE's in contour form showing various measures and their relationships during the implementation period of a given signal control plan, as shown in Figure 12.4
- Graphic charts and tables of aggregate MOE's by section and systemwide for an entire 24-hr period (or during the normal computer control period)
- A list of the worst links, sections, etc., based on MOE and time-of-day, day-of-week oriented
- The posting of some pertinent MOE's on a daily basis to keep all personnel aware of the importance of the quality of traffic flow in the system

An important element of data collection and analysis is to establish a structured procedure whereby reviews of current MOE's and other data are scheduled and assigned to a specific individual or team. In this way, a timely review of the ever-changing traffic patterns in the typical system and the subsequent actions needed to improve operation is assured.

System Modification and Updates. Traffic control systems, regardless of their size, sophistication, or their degree of complexity, require changes in operation. Control strategy and timing modifications, operating and control software updates, and the addition of new control features in the form of hardware or software are all examples of system upgrading. Each of the described system modifications have different time-frame cycles and are done for reasons unique to each of their characteristics.

Updating System Timing — In the case of the TCS which has no surveillance features, the traffic engineer relies on field data acquired manually for timing plan updates and modifications. He may, however, have the opportunity to use these data, together with the physical characteristics of the system, as input for one of several available signal timing optimization programs, such as PASSER, TRANSYT or SIGOP. These programs are available for use on small, personal-type microcomputers. They are also implemented on the larger signal system computers, offline or in parallel with system control operations. Typical loops for updating system timing are shown in Figure 12.5.

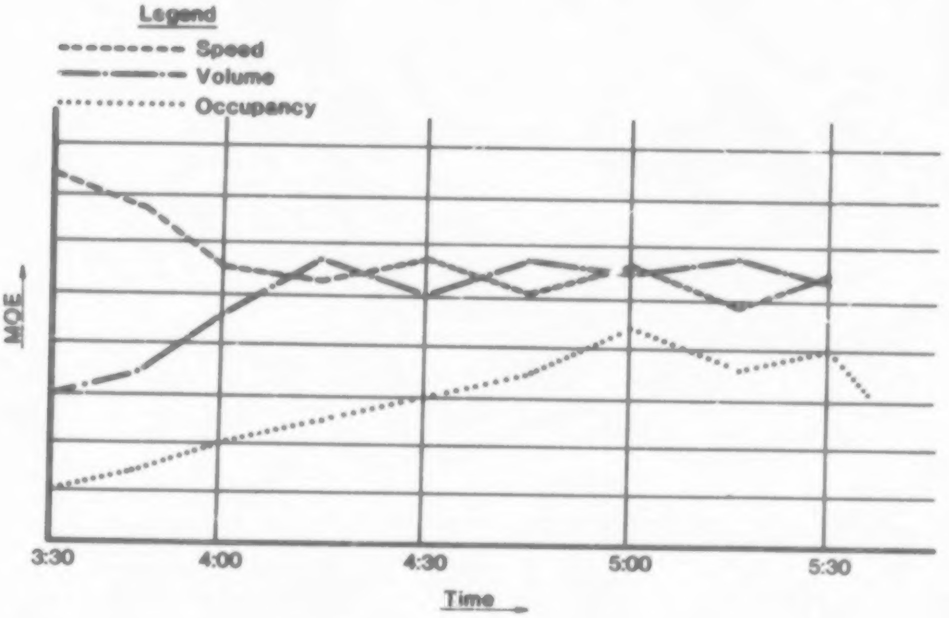
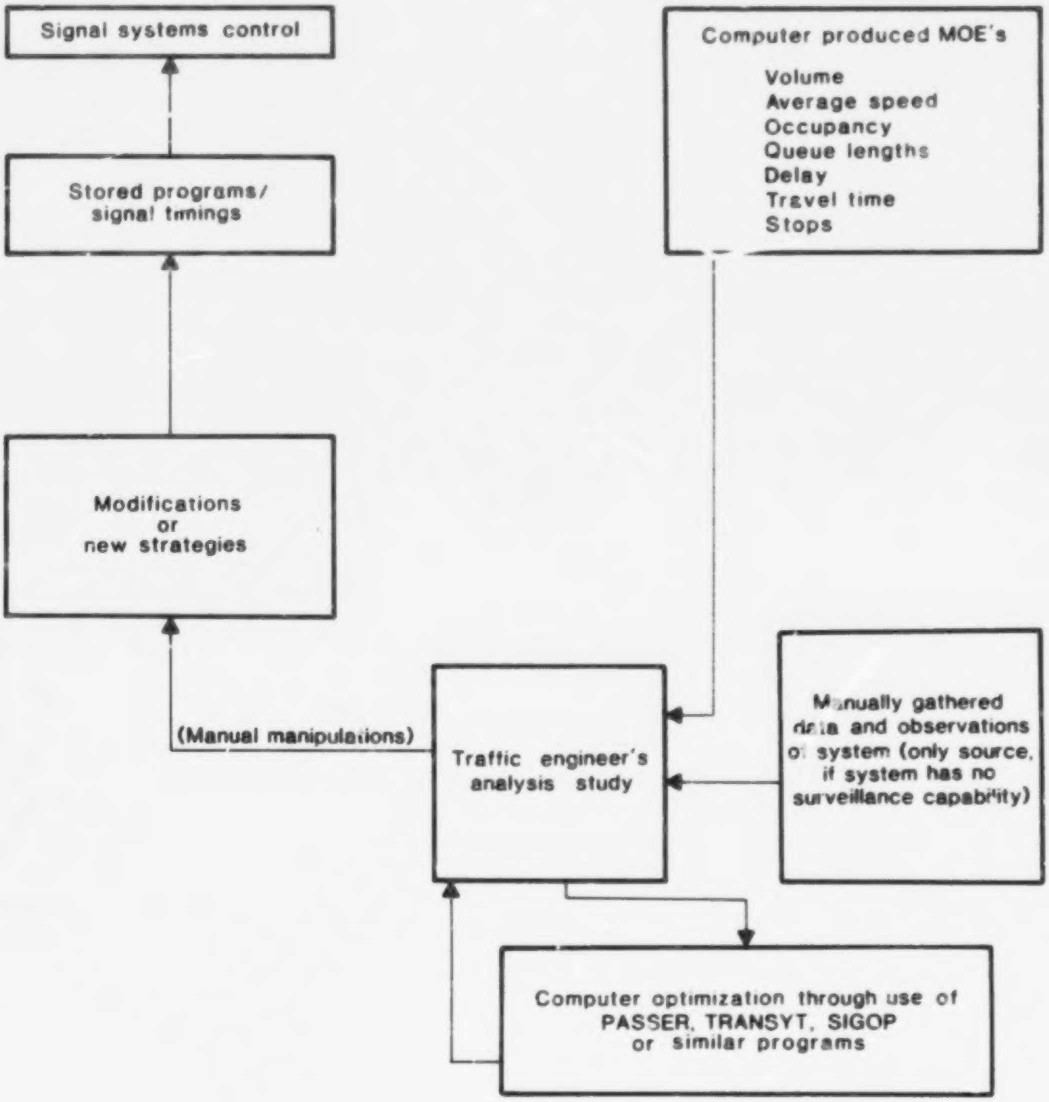


Figure 12.4. Typical aggregate MOE contour timing plan graphic

Many systems (including freeway control systems) begin operation by using relatively simple control algorithms, and some begin with a majority of controlled locations operating in the isolated or free mode. Urban street systems initially may depend on only a time-of-day pattern selection procedure, and, indeed, some systems have been operated in that mode from inception, either by design, or through failure to follow through with upgrading or updating. Most systems, however, are designed, at least in part, for dynamic control operation in which timing plans are matched to measured parameters and then implemented on that basis.

Changes in traffic flows create a need to implement signal timing changes. Land-use and population changes,



Signal systems control
Stored programs/ signal timings
Modifications or new strategies
Computer produced MOE's
Volume
Average speed
Occupancy
Queue lengths
Delay
Travel time
Stops
(Manual manipulations)
Traffic engineer's analysis study
Manually gathered data and observations of system (only source, if system has no surveillance capability)
Computer optimization through use of PASSER, TRANSYT, SIGOP or similar programs

Figure 12.5. Typical flow chart for system modification and update

369

addition or deletion of signals, development of major traffic generators, and street geometric and operational changes in a corridor, such as one-way streets, all contribute to changes in traffic flow patterns. Regardless of the cause, the signal system timing and control strategies must be adapted to new requirements. Among them are microlevel and macrolevel changes involving interval lengths, splits, offsets, metering rate (in freeway control) and duration and scheduling of control plan periods including traffic responsive operation. These changes, when done on a macro basis, will probably result in the development of an entirely new timing plan. Systems with surveillance capabilities not only provide for control plans implementation, but also produce MOE's, a means of defining the needed timing changes.

Incorporation of Software Updates — Software in a typical TCS is oriented to two different functions:

- Operating system — Software utilized to control computation functions of the computer, establish priorities for handling data, and to provide control and distribution functions for peripheral equipment, such as tape drivers, disc drives, display map drives, color graphics CRT, and control console. This software usually requires infrequent updates unless peripheral hardware is added to the control center complement. Responsibility for operating system software changes usually falls to the maintenance contractor who, in most cases, is the supplier or manufacturer of the central computer.
- Traffic control system — Software used to provide all operational and traffic control functions of the system. A wide array of user input-output options must be handled to produce the desired control strategies. In the smaller control systems, the user may never need to change or even have access to control software. In the larger computer-based systems, however, the user may need to modify or expand the system, thus access to the software is necessary. In such cases, he must have access to source programs and all logic documentation. This situation assumes, of course, that the control software has been declared nonproprietary, and that the user has full rights to use, modify, and transfer software, restricted only as stated in a specific agreement, executed during implementation procedures.

Some conditions which may predicate the need for traffic control system (TCS) software updates in some systems are listed below:

- Modification of control procedures for implementation of selectable phase sequencing
- Additions or deletions of signalized intersections in the communications network
- Changes in reporting procedures, in content, in scheduling, and in the peripheral devices to which the reports are assigned
- Modification of algorithms used in the implementation of timing plans for traffic-responsive control and for critical intersection control

In some cases, these various system changes can be accomplished via the operator's interface.

Procedures should be established for formalized testing of TCS software on a scheduled basis. Verification of correct TCS software operation is available via monitoring, but should be double-checked periodically, by visually spot-checking actual control system operation. Thorough testing must be carried out immediately after any modification is made to the TCS software.

Addition of New Control Features — The addition of new control features to a system often requires major software restructuring. Some control features which might be added are as follows:

- Capability to change the sequence of signal phases at system-controlled inter sections from one timing plan to the next; this capability could also be implemented in critical intersection control (CIC)
- Addition of CIC on a systemwide, software-selectable basis
- Addition of emergency vehicle preemption, oriented either to the use of the centrally-controlled, moving window concept, or on individual intersection control with system monitoring
- Addition of railroad crossing preemption with monitoring capabilities
- Capability to give priority to the control of high-occupancy vehicles during peak-volume periods
- Conversion of the system, or designated sections of it, from the time of day only to traffic-responsive control capability
- Addition of equipment and capability of interfacing with a freeway corridor control system
- Capability of controlling changeable message signs

The addition of certain control features involves not only software modification, but also hardware component additions, upgrading, or replacement. This hardware may include signal controller units, detector systems, communications medium components, and control-center peripherals.

When the addition of control features is contemplated, the greatest concern in the management element of the system is planning and coordination. In formulating a plan, the greatest care must be taken in the proper sequencing of tasks and in efficient, mutual utilization of effort. Thus, the periods of reversion to system backup control during installation or construction will be minimized.

Additions and Deletions of Signal Hardware — A basic premise used in the design of TCS's is the requirement that additions or deletions in the control network are readily accommodated. The predominant situation which is usually visualized during the design phase, is concerned with the desire to expand the control system to an adjacent area, or areas, which could represent a significant increase in system size.

Of equal importance is the more-frequent need — usually arising from traffic pattern shifts within the control area — to signalize a previously unsignalized intersection. Such additions obviously present a need for hardware installation of signal indications, controller assembly, and communications equipment. In addition, modifications of software data base tables and timing patterns are also required. Physical removal of individual controlled intersections likewise would require similar system changes. Traffic control systems must possess the flexibility to accommodate these changes, while making them is a typical operational task.

12.4 STAFF REQUIREMENTS AND ORGANIZATION

Increased Opportunity for Interaction

Traditionally, the operation of TCS's has tended to be either minimized or, in some cases, considered a function of the maintenance activity. It is true that there is only a very limited opportunity for an operation to interact in real time with a pretimed, nondynamic control system. Too often, however, where opportunity for interaction exists, operation tasks are relegated to fill-in or last-priority activities in the mix of those usually performed by professional traffic engineering and/or maintenance staffs.

The expanded flexibility and ever-increasing control refinement presently provided in control systems gives the user agency a unique opportunity for interaction. Unfortunately, in many of the existing systems the surface has barely been scratched, when utilization of capabilities is considered. The operating staff is as much a part of the system as the computer itself, and interaction must be a give-and-take proposition between the staff and the system, if full potential is ever to be attained.

Staffing Examples

In considering the staffing needs for various types of TCS's, the experience of currently operating systems is invaluable. Table 12.1 gives examples of staff structures in existing systems of various types and sizes.

Factors to Consider in Staffing

Regardless of control system size, the staffing structure requires two basic skills:

- The normal skills possessed by an experienced traffic operations engineer — Included are such skills as a knowledge of traffic flow principles, control concepts, and local conditions. Individuals with these skills are aware of special signal phasing requirements, preemption needs, conditions of existing equipment, and other details which are valuable during system planning, design, installation, and *operation*.
- The skill to realize the full potential and capabilities of the given control system to do its job, and to accommodate modifications — This skill level may range from a basic knowledge of a pretimed arterial system to the high-level complexities of computer programming. Nearly all agencies operating computer-based control systems have at least one person with some programming experience. While very few agencies have made changes in the ontime control system software, changes in offline programs, however, are routinely made by some agencies, such as programs to process MOE data. Some agencies rely on outside contracts with private firms for programming skills, and these applications are discussed in the software maintenance section later in this chapter.

In the assessment of staffing needs, a number of factors need to be considered in addition to the individual skills of personnel. Critically evident among these is the level of resources available. As noted in Chapter 11, providing adequate technical staff parallel with design and implementation of the traffic control system is probably the most important factor in successful operations. Staff size and capabilities are frequently proportional to the relative priority assigned to traffic operations by the agency. A serious mistake results when it is assumed that the sophistication and capabilities of a traffic control system can somehow reduce the size and/or technical talents of the staff required for its operation.

Some other significant factors to be considered in staffing include the following:

- Assignments — In some of the smaller TCS's, many of the typical operational tasks can be performed by one or two qualified individuals. However, in larger

Table 12.1. Examples of staffing for management of computer-controlled systems

City of Dallas (Texas)	177 intersections under supervision of central computer — projected expansion to 1,000 intersections
	Department of Transportation Traffic Systems Division Assistant Director of Transportation
Operations	Traffic Control Systems Operations Division Traffic control system supervisor — 2 Traffic control system operator — 3 Programmer/analyst — 1 Keypunch operator — 1
Maintenance	Computer and peripheral equipment maintenance is by contract — annually renewed through bidding process — quick response by local personnel required Balance of system, including field communications system, modems, and controllers, by in-house technicians in signal maintenance division
City of Las Vegas/Clark County (Nevada)	Multijurisdictional central/distributive computer control system, 260 intersections under central and jurisdictional control
Three entities	City of Las Vegas Clark County City of North Las Vegas
Operations	Traffic Management Center Systems manager Transportation engineer/systems analyst System operator
	Jurisdictional Management Centers City of Las Vegas: System portion within jurisdiction monitored during working hours by engineering technician Clark County: System portion within jurisdiction monitored during working hours by traffic engineer City of North Las Vegas: System portion within jurisdiction is monitored on a part-time basis by available personnel
Maintenance	TMC - Computer and peripherals by contract — quick response JMC - Computer and peripherals — as needed, by local maintenance firms Balance of system, including communications hardware, modems, controllers and modification kits, is done by technicians in respective jurisdiction where equipment resides

systems, specific tasks must be identified and assigned to appropriately skilled personnel. Individual team members must be made aware of their specific responsibilities and their interdependent relationships with other team members necessary for proper system operation, and updating.

As the size and operational characteristics of a system change, the scope and character of assignments must be altered if desired operation is to be maintained. Although tasks and their assignment must be clearly defined, a certain flexibility should be retained to permit some overlap in responsibilities. Individual talents and experience are thus increased through exposure to a variety of tasks, and overall interest in system operation and updating is spurred.

Some special tasks, not directly applicable to system operation, are usually assigned to the systems operation team. Included are the following:

- Scheduling, supervising, and conducting in-house, on-the-job training programs
- Hosting visitors to the control center — a task which is usually most intense during the first 18 months of operation

  - Developing public relations and citizen-information programs through press releases, or by compilation and printing of literature, based on the operation and performance results of the control system

- Shifts — Traffic control systems perform their functions around the clock, handling their more critical traffic loads during recurring control periods of higher demands. Most current operating systems provide on-site personnel for operations duties covering at least the period from the beginning of the morning peak to the end of evening peak. Some systems limit staffing periods to peaks only.

  The proper staffing periods for a given control system can be determined only by experience with the system's operation over a reasonable period of time. As a starting point, however, a 2-shift operation covering the period from approximately before the onset of the morning peak to the end of the evening peak should be provided, supplemented by some form of alarm response for the balance of each 24-hr period. It is important to staff the TCS an hour before the morning peak in order to clear possible system problems, restore and repair controllers to online status, alert maintenance personnel, and to have available if an event occurs which requires manual intervention before the very heavy demands are in need of control.

  Ideally, operators would be supervising the larger systems during all times of operation, 24 hr/day. However, in the majority of cases, that approach is neither practical nor justifiable from a budgetary viewpoint. In a few control systems now in operation, the staffing (at appropriate force levels) is maintained on a 24-hr basis. But this is the exception rather than the rule.

- Training — When systems are initially installed, a typical practice is to require that specific training be provided by the system installation contractor (see Chapter 11). This training is extremely valuable and is a valid requirements for inclusion in system implementation.

  The ongoing training element must be addressed by the systems manager because of personnel turnover, advancement of personnel to other positions, or terminations of employment. A regular in-service and on-the-job training program should be initiated as soon as practical after system implementation. Such a program provides continuity of operation as personnel changes occur, and tends to increase general interest in the total operation picture among team members.

Organization

Logically, organization of a TCS team should be centered around a nucleus of a functioning traffic operations section or division of a transportation department (or an equivalent section of a comparable entity). In that nucleus lies the essence of system traffic control — day-to-day and year-to-year practical experience. With this organizational structure, present operations personnel can absorb the new traffic control tool into their operations and, with proper training, utilize it to achieve performance improvements in the street system. Likewise, new personnel incorporated within the team structure stand to benefit from the practical experience of longer term personnel.

To ensure closer coordination and cooperation, it is advantageous for the same organization which has responsibility for operations to have the responsibility also for maintenance. This logical tie-in of two essential system management functions improves the cohesion necessary in a team-concept approach.

12.5 MAINTENANCE OF TRAFFIC CONTROL SYSTEMS

The successful performance of any operational traffic signal control system is dependent on the commitment of the operating entity to an effective maintenance management program. All too often, however, maintenance becomes an underemphasized function of TCS management. Typically, the underlying problem is that adequate funding, budget, and staffing resources (appropriate for the design) are not made available. Eventually, poor maintenance management results in a degraded level of TCS performance, and the system is ultimately seen as a failure by the general public.

Many operational TCS's evolved with only minimal examination of recurring annual costs associated with their maintenance requirements. Some agencies have erroneously presumed that high-technology TCS's possess fewer maintenance requirements, and consequently underestimated budget and staffing needs for proper system maintenance. Similarly, agencies have failed to recognize the higher personnel skill levels required to maintain complex TCS's. This fact emphasizes the need for cost tradeoff analyses to cross-examine those design factors and maintenance management policies which could reduce maintenance requirements and still provide an effective maintenance program.

Accurate recordkeeping and overall system configuration documentation, which includes up-to-date timing plan, data base, software, and hardware information, is a prerequisite to the development of an effective maintenance management program. The task of maintaining an accurate information system requires that updating be done on a daily basis. These records will prove invaluable in the special event of litigation and, of course, are a necessity in predicting future maintenance needs or performing a realistic cost analysis.

In considering the varied requirements of TCS maintenance, the intent of this section is not to describe the technical elements of maintenance. For such details, the reader is referred to the specific maintenance manuals for system components normally provided by the manufacturer or vendor. Rather, this section focuses on the management aspects of TCS maintenance.

Types of Maintenance

Traffic control system maintenance activities can be categorized into the three following types:

- Functional
- Hardware
- Software

Each of these types of maintenance activities is described more fully in the following discussion.

Functional Maintenance. The major objective of any TCS, regardless of the degree of advancement in functional capability, is to enhance the quality of vehicular traffic flow. If this objective is to be achieved, a continuing effort should be expended on updating the data base and the optimization of signal timing plans. These two elements of TCS maintenance are a major impact to system staffing and cost requirements, the importance of which cannot be overemphasized.

In order to capture continuously all the benefits which accrue to improved traffic performance, signal timing plans must be updated to reflect changes in traffic demands and travel patterns. The resource (personnel, equipment, expenses) requirements for conducting a signal timing optimization project have been well documented by extensive research (*1*). Table 12.2 summarizes expenses for a sample network, although the figures can be considered higher than what would normally be required if experienced lower-level staff were utilized as much as possible.

Computer-based TCS's utilize extensive data base subsystems which define system control input parameters, operating thresholds, functional characteristics, hardware characteristics, etc. These elements should be updated whenever required. Typical requirements for data base updates include the following:

- Detector relocations
- Section reconfiguration
- System expansion
- Changes in controller types
- Changes in preemption routes

Hardware Maintenance. Traffic control system hardware maintenance generally falls into three categories (*2*). The first, and usually the one commanding the highest priority, is remedial maintenance required as the result of malfunction and equipment failures, including emergency repair activity to restore operation. The next is preventive maintenance — those work items that should be done at scheduled intervals to minimize the probability of failure. Then there is modification or reconstruction which becomes necessary when a manufacturing/design flaw is identified or hardware improvements are needed to improve equipment characteristics.

In any TCS hardware maintenance staffing and budgeting requirements represent a disproportionately high share of the overall maintenance budget allocation because of the labor-intensive nature of hardware maintenance activities, the sheer magnitude of field equipment and system master components present in most systems, and the need to maintain sufficient spare equipment for continuous system operation. The maintenance requirements for field equipment and system masters differ in accordance with function, design complexity, and operating environment. In general, however, field equipment requires a higher degree of maintenance activity and, therefore, more management attention.

Field Equipment — The maintenance of field equipment in TCS's has changed dramatically with the advent of microprocessor-based local controllers and widespread utilization of computer control systems. In particular, data communications subsystems and special devices such as changeable message signs and television surveillance equipment account for the substantial increase in maintenance activity associated with advanced TCS's. Detectors are of the same type already in widespread use; nevertheless, an increase in the number of units can be expected with implementation of most advanced TCS's. Microprocessor-based local controllers and other such technical electronic system devices have introduced the need for a higher skill level among maintenance staff as well as more complex troubleshooting techniques and test equipment. Local controllers which

374

Table 12.2. Summary of 1982 expenses for timing a 46-intersection network

	Personnel				
Activity	Time (Man-Days)		Cost (Dollars)	Cost of Other Expenses (Dollars)	Total (Dollars)
Initial startup	20.3		$1,925	$1,470[a]	$3,395
Preparation of data collection plans	7.8		700	—	700
Data collection and reduction	19.7	h/int.	7,320	320	7,640
Data coding	3.3	h/int.	1,660	1,660	
Running TRANSYT-7F	4.1	h/int.	2,025	1,240[b]	3,265
Installation and fine tuning	3.9	h/int.	2,120	1,470[b]	3,590
Miscellaneous	7.5		685	35	720
Total	N/A		$16,435	$4,535	$20,970[c]

[a] This cost assumes a $1,200 expense for travel to a training course and $270 expense for payment for in-house computer services.

[b] This cost assumes payment is for in-house computer services.

[c] The average per intersection would be $20,970/46 = $456 per intersection.

Source: Reference (*1*)

are operated as part of a coordinated system should be examined regularly to validate both the system and the free operational modes for signal efficiency. Interconnect equipment, including communication modems, should be inspected concurrently.

Technical advancements in the electronics industry should, in theory, mean more reliable field equipment with less maintenance. However, this does not reduce the need for scheduled traditional maintenance activities such as relamping and inspection of poles, foundations, wiring, signal heads, and pedestrian pushbuttons. It is of particular importance that operating agencies recognize the special training skills that become necessary as technology progresses in order to prevent maintenance requirements from outstripping available maintenance capability.

System Masters — The complexity of system master hardware may range from a single-dial, pretimed electromechanical controller to an advanced digital computer. The maintenance requirement, therefore, varies with the complexity of the equipment used. The operating environment also influences the maintenance needs, since system masters may operate in the remote cyclical outdoor environment of a street corner or in the controlled environment of a computer control center.

Remotely located system masters may exhibit many of the maintenance requirements normally associated with local controllers, while more complex microcomputer-based system masters require higher-than-normal maintenance skills and more complex electronic component test equipment. Regardless of their design complexity, all system masters should be examined on a monthly basis with particular emphasis on operations, timing, and system-sensor performance. Each subordinate system local controller should be checked to verify its operation with respect to the system master. The majority of remotely located system masters generally are maintained by staff personnel; however, a number of remote system masters which are general-purpose minicomputers adapted to perform traffic control functions have been housed in thermostatically controlled facilities maintained by the computer manufacturer or an independent service firm.

In the case where the system master is a minicomputer system located in an office, a universal practice is to contract its maintenance and that of its peripheral devices. Such contracts are made with the hardware manufacturer (or subsidiary), or with an independent service firm. It is often advantageous to an operating agency to procure contract maintenance, since the computer manufacturer can upgrade hardware along with routine preventive maintenance. This method also allows for minimum downtime since component replacement is faster than repair and cheaper than the agency maintaining spare hardware components which may become obsolete with technological advancement. A third advantage is that a properly executed maintenance contract can specify a predetermined response time. Typical contracts provide for both routine and emergency maintenance, including parts and labor, on a fixed monthly fee basis. It is also possible to obtain such services on a time-and-materials basis, or combinations of the two. Fixed-fee agreements, however, are the type predominantly used.

Nonperipheral hardware equipment, such as wall map displays, is normally maintained by staff personnel.

Software Maintenance. The maintenance aspect of TCS software, is often overlooked in assessing total system maintenance requirements. Historically, decisionmakers have erroneously presumed that software programs for computer control systems are a one-time cost, with little or no maintenance required following installation. The problem is that, although these programs are represented as complete packages, it is common for software packages to experience isolated failures or bugs. The logic paths of a computer program are highly complex, and it is impossible to test and debug every possible logic path of a computer program. However, with multiple user experience over time, these problems are minimized and warranties are very important for this reason.

Even though software failures may never be totally eliminated from an operating package, the resulting problems can be reduced to manageable proportions. Some guidelines (*3*) which, if utilized, can help relieve the problems are as follows:

- First and most importantly, specify proven software. The UTCS development problems are typical of those found with any system. Let someone else deal with these problems and pay the price for doing so.
- Use a compiler-level language such as FORTRAN, where possible, rather than assembly language. This will encourage use of straightforward programming techniques. It will also simplify the task of error analysis and correction.
- Maintain software with complete and accurate documentation. The features that must be included in this documentation during the design and installation phase of system development have already been discussed. During the O&M phase, documentation of all software and data bases *must* be kept up to date.
- Maintain operating logs continuously and save for at least a year. The operating logs include exception reports, written reports of all repairs, and hardware/software changes.
- Monitor environmental conditions. The control center may have recorders that keep track of temperature and voltages. This is important because it is often difficult to determine whether the cause of failure is a hardware or a software malfunction. The recorders will provide an indication of the possibility of marginal equipment operation.

Carrying out the above procedures should enable the programmers to recreate the erratic condition that has been diagnosed as a possible software malfunction. Software testing and debugging is accomplished by a highly trained systems analyst/programmer familiar with real-time programming techniques and with the functional characteristics of the software being tested. The programmer's tools, which consist of diagnostic programs, trace programs, and dump programs, are part of the system software package provided by the computer manufacturer. All of these tools and others not identified *are critical* to the effective maintenance of the software. Their availability should be specified and evaluated during the system design and installation process.

Software maintenance includes more than just the correction of program errors. This maintenance includes a continuing process of program modification or refinement because of either physical changes in the system or enhancements to system operation.

Results of Inadequate Maintenance

The serious implications of an inadequate maintenance program are evident in a number of ways. For example, signal failures have a direct impact on accident potential. In those cases where accidents do occur, increased findings now hold the operating agency liable because malfunctions were not corrected in a timely manner. This development alone has resulted in increased emphasis on both maintenance and maintenance-records systems.

Of equal significance is the impact of adequate maintenance on the ability of a control system to perform its functions with optimum effectiveness. Failure of a single component may cause a degradation of system performance. For example, the selection and implementation of timing plans is usually dependent on input data from selected detectors. The failure of such critical detectors could result in the implementation of an inappropriate timing plan.

Maintenance deficiencies also result in the following types of equipment failure:

- Malfunction — Any event that impairs the operation of a control system without losing the display and sequencing of signal indications to all approaching traffic. Malfunctions include timing failures, detector failures, loss of interconnected control, and other similar occurrences.

- Breakdown — Any event that causes a loss of signal indication to any or all phases or traffic approaches. Included as breakdowns are controller failures, cable failures, loss of power, etc. The classic example, however, is the signal lamp burnout which leaves no indication visible.
- Reduced life — Lack of maintenance can also be expected to reduce equipment service life drastically.

Staffing for Maintenance

Agencies currently involved in preliminary maintenance staff planning for a TCS must consider not only the impacts in maintenance activities associated with an advanced TCS, but also the attendant maintenance skill-level requirements for the new system. The planning phase of system development should include an assessment of (1) both present and projected maintenance skill-level require ments, (2) present maintenance capability with respect to staffing, equipment, training, and budget, and (3) projected workload impact associated with the new TCS.

Maintenance Skills Required. The key to an effective maintenance management program is a staff of well-trained and experienced personnel. More sophisticated TCS's often require specialized training for existing technicians or the expansion of staff to accommodate specialists, such as with computer, communications, and surveillance technologies. Competent specialists are hard to find, and the salary competition for such personnel is high between governmental agencies and private industry. For this reason, agencies planning for complex computer control systems should consider the alternative of contractual maintenance services. In cases where additional staff training and expansion are deemed appropriate, the training should be thorough, include both classroom training and hands-on training, and provide intensive training in troubleshooting and diagnostic techniques.

Assessment of Present Capability. The first step toward determining projected maintenance staffing requirements must provide for an assessment of current maintenance requirements. Existing service records should be utilized to establish mean time between failure (MTBF) and mean time to repair (MTTR) data for each item of existing equipment. The ultimate result of all the computations will be the number of person-hours required to stay even with current system maintenance needs over a year's time. These calculations do not take into account multiple failures, which often occur; therefore, approximately 30 percent (*3*) should be added as a contingency in developing total staffing requirements.

The assessment of present maintenance capability would not be accurate if it did not include a concurrent appraisal of service and test equipment capability. Skill and experience cannot replace the advantage of having appropriate tools and equipment to do the job.

Workload Impact. Operating agencies seriously considering the development of a new TCS should be alerted to the potential workload impact associated with the candidate system. In general, the more sophisticated systems have exhibited a tendency to simultaneously increase maintenance needs and the awareness of maintenance needs.

The quantity and technological complexity of equipment associated with sophisticated TCS's contribute to this need for additional maintenance activity. The inherent problems of troubleshooting and repairing the various hardware subsystems of a computer control system can represent a significant increase in maintenance activity. The advanced-hardware-failure monitoring and malfunction-detection capability provided by advanced computer control systems require a higher and more responsive degree of remedial maintenance, and an additional level of troubleshooting is necessary to determine whether reported failures are related to hardware or software.

A survey (*4*) of 22 operational computer TCS's across the nation indicated that, as a result of the installation of their computer systems, additional professional and technician personnel were added to their maintenance staffs in accordance with the average rates shown below:

- Average no. of professionals/100 intersections = 0.10
- Average no. of technicians/100 intersections = 1.02

By and large, computer-based traffic control systems must be maintained by a combination of agency staff and contact maintenance, while simpler systems are fully maintained by staff. The division of the workload is a matter of individual policy and budget limitations. In any case, the demands of managing an effective maintenance program are ultimately the responsibility of the operating agency, and unless TCS plans do not adequately address maintenance staffing and budgeting requirements, they may be resigned to provide little more than remedial maintenance.

12.6 EVALUATION OF TRAFFIC CONTROL SYSTEMS

The evaluation element of TCS management provides the means with which to assess the performance levels of the operations and maintenance functions of the closed-loop control system discussed previously. By utilizing before-and-after data, such as accidents, travel speed, travel time, delay stops, etc., the effects of new systems, control strategies, and other operational improvements on safety and traffic flow quality may be measured. Without the evaluation element, there is no framework upon which to base comparisons of effectiveness measurements.

Evaluation techniques vary depending on their application and may include simulation as an alternative to real-world measurements. Similarly, data requirements and scientific validity needs vary depending on the measures of effectiveness being utilized, test conditions, and the nature of the improvement being analyzed. The resultant information provided by the various evaluation techniques is, of course, useful for traditional comparison of traffic parameters, but it may also be used to estimate other important performance measures such as fuel consumption and vehicle emissions, discussed previously in Chapter 3.

Need for Performance Evaluation

As previously indicated, system evaluation is one of the primary functions of a closed-loop control system. In that context, evaluation is a short-range or online function, intended to assess the immediate effects of operational strategy. In a more conventional sense, evaluation refers to the overall determination of the relative merits of system improvements.

Traffic control system improvements are usually justified to decision-makers on the basis of some forecast of the improvements or benefits which may result. The real need for evaluation, then, would be to confirm or reject the hypothesis that the expected results would occur. Such evaluations also become useful tools in the identification of ways to increase benefits further and/or justify system expansion. Further, the dissemination of the evaluation results provides user experience which is beneficial to other agencies considering such improvements.

Evaluation Techniques

Traffic surveillance and control system strategies and tactics fall underneath the umbrella of conceptual TSM actions; therefore, the first step should be the establishment of objectives which will define a desired level of performance improvement that is within the framework of broader regional goals and objectives. As discussed in previous chapters, these could take very general forms as the following:

- Improve the safety of the existing transportation system
- Reduce the travel time required on the existing transportation system
- Reduce undesirable transportation system air-quality impacts and energy consumption
- Provide rapid detection and removal of capacity-reducing accidents
- Increase person movement capacity of the existing transportation system to serve demand

The second step in the TSM planning process provides for the selection of appropriate MOE's that will serve as a basis or standard of comparison. In turn, the MOE's selected will define the form of the data needed to evaluate strategies/tactics and to structure the before-and-after studies.

Either manual- or computer-simulation techniques may be utilized for evaluating strategies or tactics. However, computer-simulation models must be thoroughly calibrated, and it is probable that significant staff resources and time will be consumed before accurate MOE estimates can be calculated. The staff and budget requirements to conduct the evaluation using either computer or manual estimation procedures are heavily dependent on several factors, as follows: the proposed strategies/tactics, the size of the affected area, the number of alternatives to be considered, and the specific models used.

The most important factor is the level of staff capability and the familiarity of the staff with the models under consideration. Experience indicates that the cost of the evaluation effort will be underestimated when an unfamiliar procedure is being evaluated. Consequently, care should be exercised to assure the most cost-effective procedure is selected.

Before-and-After Measurements. Measurement of conditions before and after project implementation is perhaps the most common and simplest approach for evaluating improvements. Basically, this approach establishes the before measurement as the base and assumes that the after conditions represent the effect of the improvement being tested.

This approach is particularly susceptible to errors caused by time-related factors, especially if the effects are measured over a long period. Factors such as population

378

growth, economic fluctuations, or other changes, may influence conditions between the measurements taken before and after. Reliance on before-after measurements as indicators of change also makes it difficult to identify how much of the change is attributable to individual improvements made at the same time — a confounding effect. Assessment of what portion of an accident-reduction effect is attributable to each of the following:

- The installation of improved signal indications
- Control system improvements, since both were implemented at the same time

Simulation Analysis. A number of network analysis techniques utilize computer simulation of vehicular travel to evaluate alternative strategies and tactics. These various simulation and/or signal optimization programs, such as NETSIM, FREQ, TRANSYT-7F, and SIGOP-III, represent a battery of powerful analytical MOE estimates for analysis. Data input requirements, staff resources and capability, and cost are the principal deterrents to their use in most evaluation studies. Essentially computer-simulation techniques are more suitable under the following conditions:

- The proposed strategies are likely to impact large geographic areas (e.g., corridors, entire CBD, region).
- Many interrelated strategies are being studied and the analysis methods are complex or involve numerous calculations.
- The proposed strategies can be represented by the independent variables in available simulation models.
- Many alternatives are being considered in a given subarea.

Validity of Measurements

For traffic surveillance and control system projects, several common factors are likely to jeopardize the success of the evaluation of individual projects. Other factors may limit the applicability of the results to other metropolitan areas. Campbell and Stanley (*5*) have identified such factors as threats to internal validity. A thorough understanding of these threats to the validity of evaluation results, together with a clear recognition of project goals, is essential to a well-developed evaluation.

Threats to Internal Validity. To be internally valid, the study must be designed so that the strategy being tested produces an identifiable response, and so that the influence of this strategy on the response can be separated from the influence of other strategies or factors. In transportation-oriented projects, the following potential problems should be considered carefully in planning for both the implementation and the evaluation of the strategy:

- Confounding of effects — Confounding refers to mixing two or more techniques, test conditions, or other factors so that the effects of each cannot be isolated or measured separately.

  A widespread problem with traffic surveillance and control projects is the concurrent implementation of two or more techniques (such as roadway improvements, one-way streets, modified signal indications, and revised timing patterns) intended to reduce congestion. If a net change in congestion is observed, it may be impossible to identify the influence of each strategy. In other cases, the effects of the control system improvements may be confounded with effects of other external factors, such as subway construction in the CBD, roadway construction in other areas, or erratic growth patterns.

  Selection of measures of effectiveness — The characteristic (e.g., cost, travel times, accident rates, etc.) which is chosen for measuring the effectiveness of a strategy must be sensitive or responsive to that strategy improvement. Similar types of strategies in different areas may not produce measurable responses in the same characteristic; or, the scale of these responses may differ (e.g., changes in travel time through a bottleneck versus change in total trip time through the corridor). The MOE for a particular project must also be selected in accordance with the project objectives.

- Stability of effects and length of time required for monitoring such effects — A staged implementation of projects must permit enough time between stages to monitor the effects of different combinations of improvement strategies. Where significant long-term changes are anticipated and it is desired to monitor them, the evaluation must be continued.

Threats to External Validity. Those factors which restrict the applicability of the findings from the individual project to other project areas and cities may be termed threats to external validity. In the context of a traffic surveillance and control project, potential threats to external validity would include the following:

- Suitability of techniques being tested for use in or application to control areas and urban areas — Many control system projects have conditions or problems that are unique. These include topographical constraints and the characteristics of transportation demands. The results of strategies aimed at these localized problems may have little value in helping other urban areas solve their transportation problems.

- Identification of factors that influence the effectiveness of the techniques being tested — Factors that influence the success of the individual project must be thoroughly documented in terms of characteristics that can be readily measured in other project areas or urban areas.

Sampling Considerations. The integrity of the sampling technique used for data collection is vital to the level of precision expected in the evaluation. The level of precision associated with a before-and-after study will depend on the importance of detecting a difference, the expected size of the difference, and the cost of the data-collection activity.

High precision may be warranted by the importance of the project in cases involving research. High precision may also be required for studies involving relatively small before/after differences, simply because a small-scale study would be a waste of effort. Relatively lower precision can be accepted for studies involving major changes at a particular location. A careful design of the sampling procedure is required to measure the effects of the alternative strategies efficiently and accurately.

The data and sampling techniques which are appropriate for the design of routine projects are usually inadequate for the evaluation phase. The use of available or routinely collected data also may pose a significant threat to the validity of the experiment unless sufficient assurance is provided that these data satisfy the requirements for project evaluation.

Categories of Data Required

The analysis data required for evaluation of alternative traffic surveillance and control system strategies can be stratified according to the following categories:

- Improvements
- Test conditions
- Measures of effectiveness

Descriptions of Improvements. Candidate strategies should be thoroughly defined in study documentation, prior to commencing data collection. It is of paramount importance to the success of the study that MOE-strategy relationships are clearly understood. Further, this assures the existence of a historical record for future reference.

Descriptions of Test Conditions. It should be apparent that any analysis of urban travel characteristics must consider the system characteristics of the transportation network. That is to say that the interrelationship among all network roadways must be examined concurrently. Prevailing urban socioeconomic data that influences the results of each project must be identified and documented.

In describing these characteristics, precise data relating to population and employment distribution are necessary if the study area is large. The data should be general but comprehensive. Collection of extensive data of this nature is not likely to be justified solely for the purposes of the demonstration; however, the necessary information is generally available from local urban transportation studies or the local metropolitan planning organization (MPO) agency.

Descriptions of Measures of Effectiveness (MOE's). Measures of effectiveness appropriate to the evaluation of traffic surveillance and control systems fall into four general categories:

- Changes in congestion levels and travel patterns, reflected through factors such as volume measurements, travel time family of measures (speed, stops, delays, etc.), and duration of congestion
- Changes in system operation costs, both to the user and the system operator
- Community effects, evidenced by factors such as decreased accident rates
- Improved accessibility, evidenced by decreased delays, and increased economic activity

The process of selecting the final MOE's for analysis and evaluation is likely to be an iterative one requiring subjective compromises between the 'best' MOE's, the availability and accuracy of estimation and data-collection techniques, and schedule, staff, and budget constraints. An important step in selecting a final set of MOE's is ensuring that those provided are important and are understandable to elected officials, administrators, citizens, and other affected groups.

In selecting the final MOE's and the data collection and estimation procedures, it is important to note the following:

- The impacts of many alternative strategies are frequently small in both absolute and percentage terms
- The impacts frequently are confined to a small geographic area
- It may not be possible to develop highly accurate, site-specific impact estimates using commonly available data and estimation procedures

In developing MOE's, it will be helpful to review the set of criteria presented in Table 12.3.

The MOE's which are commonly measured and computed from surveillance data of traffic performance measures include the following:

- Total travel time
- Total vehicle-miles of travel
- Number and percentage of stops
- Delay
- Corridor throughput
- Total minute-miles of congestion
- Accident rate reduction

These MOE's are used to indicate the improvement in efficiency of traffic flow resulting from a particular control strategy or tactic. One cannot overemphasize the importance of utilizing accepted statistical methodology to verify the accuracy and level of confidence associated with comparative analysis results when evaluating before-and-after MOE data. For a more detailed description of the basic methods of field data collection and the mathematical derivation of these measures of effectiveness, the interested reader should examine the suggested reference documents (*7-8*).

Table 12.3. Criteria for developing measures of effectiveness (MOE's)

- Relevancy to objectives: Each MOE should have a clear and specific relationship to transportation system management (TSM) objectives in order to ensure the ability to explain changes in the condition of the transportation system.
- Simple and understandable: Within the constraints of required precision and accuracy, each measure of effectiveness (MOE) should be simple in application and interpretation.
- Quantitative: MOE's should be specified in numerical terms whenever possible.
- Measureable: Each MOE should be suitable for application in pre-implementation simulation and evaluation (i.e., have well-defined mathematical properties and be easily modeled) and in post-implementation monitoring (i.e., require simple direct field measurement attainable within reasonable time, cost, and manpower budgets).
- Broadly applicable: MOE's which are applicable to many different types of strategies should be used whenever possible.
- Responsive: Each MOE should be specified to reflect impacts on the various actor groups, taking into account, as appropriate, geographic area and time period of application and influence.
- Sensitive: Each MOE should have the capacity to discriminate between relatively small changes in the nature or implementation of a control strategy.
- Not redundant: Each MOE should avoid measuring an impact that is sufficiently measured by other MOE's.
- Appropriately detailed: MOE's should be formulated at the proper level of detail for the analysis.

Source: Reference (*6*)

REFERENCES

1. Federal Highway Administration and the University of Florida. *National Signal Timing Optimization Project: Summary Evaluation Report*. Washington, D.C., May 1982.
2. Baxter, Daniel. "Contracting Maintenance for Traffic Signal Systems." New York State Department of Transportation, August 1984.
3. PRC Voorhees. *Computer Controlled Traffic Signal Systems*. Federal Highway Administration, Washington, D.C., 1982.
4. Gordon, Robert L. "Survey of Operational Computer Traffic Systems." *CCSAG Newsletter*, April 1982.
5. Campbell, Donald T., and Julian C. Stanley. *Experimental and Quasi-Experimental Designs for Research*. Rand McNally and Co., Chicago, 1966.
6. Abrams, Charles M., and John F. Direnzo. Vol. 2: *Measures of Effectiveness for Multimodal Urban Traffic Management*, 1979.
7. Federal Highway Administration. *TRANSYT-7F User Manual*. Washington, D.C., April 1981.
8. Box, Paul C., and Joseph C. Oppenlander. *Manual of Traffic Engineering Studies*. Institute of Transportation Engineers, Arlington, Virginia, 1983.

APPENDIX A

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
WASHINGTON, D.C. 20590

FEDERAL AID HIGHWAY PROGRAM MANUAL

TRANSMITTAL 376
April 2, 1984
HTO-22

1. MATERIAL TRANSMITTED. Volume 6, Engineering and Traffic Operations; Chapter 8, Traffic Operations; Section 3, Traffic Control; Subsection 4, Traffic Surveillance and Control.

2. COMMENTS. FHPM 6-8-3-4, which provides policies and procedures relating to Federal-aid requirements of traffic surveillance and control system projects, has been revised to:

   a. reduce redtape and eliminate unnecessary requirements, while at the same time ensuring the achievement of optimal system performance;

   b. include a policy statement to underscore the significance of traffic control measures and to emphasize the importance of efficient system performance;

   c. require the development of an operations plan as part of the traffic engineering analysis; and

   d. include system start-up activities as an eligible item for Federal-aid funding.

3. ITALICIZED MATERIAL. The italicized material in the attached directive is published in the Federal Register and codified at 23 CFR Part 655.

Ray Barnhart
R. A. Barnhart
Federal Highway Administrator

DISTRIBUTION: H-WXE-9
H-XE-10(Volume 6)

Federal-Aid Highway Program Manual
Transmittal 376, April 2, 1984

FILING INSTRUCTIONS

Page Changes

Remove	Insert
1 through 10 of Vol. 6, Ch. 8, Sec. 3, Subsec. 4, dated 9/27/74 and 9/10/76	1 through 4 of Vol. 6, Ch. 8, Sec. 3, Subsec. 4

U. S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

FEDERAL-AID HIGHWAY PROGRAM MANUAL

VOLUME	6	ENGINEERING AND TRAFFIC OPERATIONS
CHAPTER	8	TRAFFIC OPERATIONS
SECTION	3	TRAFFIC CONTROL

SUBSECTION 4 TRAFFIC SURVEILLANCE AND CONTROL

Transmittal 376
April 2, 1984
HTO-22

Par. 1. Purpose
2. Authority
3. Traffic Surveillance and Control Systems
4. Policy
5. Eligibility
6. Traffic Engineering Analysis
7. Project Administration

1. PURPOSE. **To provide policies and procedures relating to Federal-aid requirements of traffic surveillance and control system projects.*

2. AUTHORITY. *23 U.S.C. 101(a), 135(b) and 315; 49 CFR 148(b).*

3. TRAFFIC SURVEILLANCE AND CONTROL SYSTEMS

   a. *A traffic surveillance and control system is an array of human, institutional, hardware and software components designed to monitor and control traffic, and to manage transportation on streets and highways and thereby improve transportation performance, safety, and fuel efficiency.*

   b. *Systems may have various degrees of sophistication. Examples include, but are not limited to, the following systems: traffic signal control, freeway surveillance and control, highway advisory radio,*

*Italicized material is published in 23 CFR Part 655.

reversible lane control, tunnel and bridge control, adverse weather advisory, remote control of movable bridges, and priority lane control.

c. *Systems start-up is the process necessary to assure the surveillance and control project operates effectively. The start-up process is accomplished in a limited time period immediately after the system is functioning and consists of activities to achieve optimal performance. These activities include evaluation of the hardware, software and system performance on traffic; completion and updating of basic data needed to operate the system; and any modifications or corrections needed to improve system performance.*

4. POLICY. *Implementation and efficient utilization of traffic surveillance and control systems are essential to optimize transportation systems efficiency, fuel conservation, safety, and environmental quality.*

5. ELIGIBILITY. *Traffic surveillance and control system projects are an integral part of Federal-aid highway construction and all phases of these projects are eligible for funding with appropriate Federal-aid highway funds. The degree of sophistication of any system must be in scale with needs and with the availability of personnel and budget resources to operate and maintain the system.*

6. TRAFFIC ENGINEERING ANALYSIS. *Traffic surveillance and control system projects shall be based on a traffic engineering analysis. The analysis should be on a scale commensurate with the project scope. The basic elements of the analysis are:*

   a. *Preliminary Analysis. The Preliminary Traffic Engineering Analysis should determine: the area to be controlled; transportation characteristics; objectives of the system; existing systems resources (including communications); existing personnel and budget resources for the maintenance and operation of the system.*

b. *Alternative Systems Analysis.* *Alternative systems should be analyzed as applicable. For the alternatives considered, the analysis should encompass incremental initial costs; required maintenance and operating budget and personnel resources; and expected benefits. Improved use of existing resources, as applicable, should be considered also.*

c. *Procurement and System Start-up Analysis.* *Procurement and system start-up methods should be considered in the analysis. Federal-aid laws, regulations, policies, and procedures provide considerable flexibility to accommodate the special needs of systems procurement.*

d. *Special Features Analysis.* *Unique or special features including special components and functions (such as emergency vehicle priority control, redundant hardware, closed circuit television, etc.) should be specifically evaluated in relation to the objectives of the system and incremental initial costs, operating costs, and resource requirements.*

e. *Analysis of Laws and Ordinances.* *Existing traffic laws, ordinances, and regulations relevant to the effective operation of the proposed system shall be reviewed to ensure compatibility.*

f. *Operations Plan.* *The final element in the traffic engineering analysis shall be an operations plan. It shall include needed legislation, systems design, procurement methods, construction management procedures including acceptance testing, system start-up plan, operation and maintenance plan. It shall include necessary institutional arrangements and the dedication of needed personnel and budget resources required for the proposed system.*

7. PROJECT ADMINISTRATION

a. *Prior to authorization of Federal-aid highway funds for construction, there should be a commitment to the operations plan (see paragraph 6f).*

b. *The plans, specifications, and estimates submittal shall include a total system acceptance plan.*

c. *Project approval actions are delegated to the Division Administrator. Approval actions for traffic surveillance and control system projects costing over $1,000,000 are subject to review by the Regional Administrator prior to approval of plans, specifications, and estimates.*

d. *System start-up is an integral part of a surveillance and control project.*

  (1) *Costs for system start-up, over and above those attributable to routine maintenance and operation, are eligible for Federal-aid funding.*

  (2) *Final project acceptance should not occur until after completion of the start-up phase.*

ACRONYMS

AAP	Arterial Analysis Package
AHAR	Automatic Highway Advisory Radio
AM	Amplitude Modulation
ANSI	American National Standards Institute
ASCII	American Standard Code of Information Interchange
ASTM	American Society for Testing and Materials
AVL	Authorized Vehicle Lane
BALI	Basic Arterial Local Intersection
BAM	Basic Arterial Master
BASYS	Basic Arterial System
BCD	Binary Coded Decimal
BCU	Bus Classifier Unit
BEAR	Broad Emergency Assistance Radio (System)
BIT	Binary Digit
BPI	Bits Per Inch
BPS	Bus Priority System
BR	Bit Rate
Caltrans	California Department of Transportation
CMOS	Complementary Metal Oxide Semiconductor
COAX	Coaxial Cable
CATV	Cable Television
CB	Citizens Band (Radio)
CBD	Central Business District
CCTV	Closed Circuit Television
CCU	Communications Control Unit
CIC	Critical Intersection Control
CIU	Controller Interface Unit
CMS	Changeable (Variable) Message Sign
COBOL	Common Business Oriented Language
CPM	Critical Path Method
CPU	Central Processing Unit
CRT	Cathode Ray Tube
CS	Critical Subtasks
CTS	Clear to Send
DARTS	Dynamic Arterial Responsive Traffic Signal System
DBRN	Decibel Random Noise
DC	Direct Circuit; Delayed Call
DIP	Diamond Interchange Program
DMA	Direct Memory Access
DOW	Day of Week
DOT	Department of Transportation
EARPROM	Electrically Alterable Programmable Read-Only Memory
EBCDIC	Extended Binary Coded Decimal Interchange Code
EC	Extended Call
EEPROM	Electrically Erasable Programmable Read-Only Memory
EIDPS	Eureka Distributive Intelligence Progression System
EPROM	Erasable Programmable Read-Only Memory
ET	Earliest Time of Completion
FACTS	Flexible Advanced Computer Traffic Signal System
FAUS	Federal-Aid Urban System
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FM	Frequency Modulation
FMX	Frequency Multiplexing
FO	Force-Off (Command)
FORTRAN	Formula Translation
FREQ	Freeway Queues
2FS	2-Frequency State
3FS	3-Frequency State
FSK	Frequency-Shift Keying
GFE	Government Furnished Equipment
HAR	Highway Advisory Radio
HOL	Hold Online
HOV	High-Occupancy Vehicles
IC	Integrated Circuit
IDOT	Illinois Department of Transportation
IFB	Invitation for Bid
ILD	Inductive Loop Detector
IMIS	Integrated Motorist Information System
IMSA	International Municipal Signal Association

IRG	Interrecord Gap
ITAP	Isolated Traffic-Actuated Program
ITE	Institute of Transportation Engineers
LAAFSCP	Los Angeles Area Freeway Surveillance and Control Project
LED	Light Emitting Diode
LIP	Local Intersection Program
LOS	Level of Service
LSI	Large Scale Integration
LT	Latest Time of Completion; Left Turn
L1S	Level 1 (One) Supervisor
L2AC	Level 2 (Two) Area Controller
L2DM	Level 2 (Two) Display Master
MAXBAND	Bandwidth Optimization Model
MAN	Manual (Pattern Selection)
MDOT	Michigan Department of Transportation
MGVD	Magnetic Gradient Vehicle Detector
MOE	Measure of Effectiveness
M1	Milestone 1
MPO	Metropolitan Planning Organization
MPU	Microprocessing Unit
MSI	Medium Scale Integration
MSG	Main Street Green
MTBF	Mean Time between Failures
MTTR	Mean Time to Repair
MUTCD	Manual on Uniform Traffic Control Devices for Street and Highways
MUX	Multiplexer
O&M	Operation and Maintenance
OTO	Office of Traffic Operation, FHWA
NEAR	National Emergency Aid Radio
NEMA	National Electrical Manufacturers Association
NETSIM	Network Simulation
NETSIM/BPS	Networking Simulation/Bus Preemption Simulation
NSF	National Science Foundation
NSPE	National Society of Professional Engineers
PASSER II	Progression Analysis and Signal System Evaluation Routine
PERT	Project Evaluation and Review Technique
PM	Phase Modulation; Preventive Maintenance
PROM	Programmable Read-Only Memory
PS&E	Plans, Specifications, and Estimates
PSK	Phase-Shift Keying
RAM	Random Access Memory
RBM	Real-Time Batch Monitor
RDOS	Real-Time Disk Operating System
RFP	Request for Proposal
RFQ	Request for Quotation
ROM	Read-Only Memory
RTOR	Right-Turn-on-Red
RTOS	Real-Time Operating System
RTS	Real-Time System; Request to Send
SCANDI	Surveillance Control and Driver Information System (Detroit Freeway)
SIGOP	Signal Optimization; Signal Timing Organization Program
SOAP	Signal Operations Analysis Package
SPVD	Self-Powered Vehicle Detector
SSI	Small Scale Integration
ST	Slack Time
TEXAS	Traffic Experimental and Analytical Simulation
TBC	Time-Base Coordination
TCS	Traffic Control Systems
TDM	Time Division Multiplexing
TDM/FSK	Time Division Multiplexing/Frequency-Shift Keyed
TIS	Travelers Information System
TMX	Time Multiplexing
TOW	Time of Week
TRANSYT	Traffic Signal Network Study Tool
TRB	Transportation Research Board
TRRL	Traffic Research Road Laboratory
TRSP	Traffic-Responsive Plan (Generation)
TSM	Transportation Systems Management
TT	Total Time
TTY	Teletypewriter
TV	Television
UTCS	Urban Traffic Control System
UVEPROM	Ultra Violet Erasable Programmable Read-Only Memory
VDT	Video Display Terminal
VLSI	Very Large Scale Integration
VOC	Volume and Occupancy Control (Constant)
VOL	Volume
WADS	Wide Area Detection Systems
YLD	Yield

GLOSSARY

Acceleration Noise — Basic variable describing quality of service. Usually considered as the disturbance of a vehicle's speed from a uniform speed.

Acceptable Gap — Time headway between successive vehicles in a traffic stream into which another vehicle is willing and able to merge.

Access Time — The time interval between the instant at which data is called for from a storage device and the instant at which delivery of the data is completed.

Actuated Controller Assembly — A controller assembly for supervising the operation of traffic control signals in accordance with the varying demands of traffic as registered with the controller by traffic detectors.

Actuation — The operation of any type of detector (NEMA). The word operation means an output from the detector to the controller unit.

Addressing — (1) ***Computer***: A method of specifying the location (address) of an operand involved in a part of an instruction. Addresses are usually numerical and specify a register, location in storage, or other data source or destination. (See ***Direct Addressing, Indirect Addressing***.) (2) ***System***: The identification of specific intersections or locations for transmission of commands or the receipt of data. (3) ***Communications***: The process of selecting a specific receiving unit on a multidrop line so that the message can be sent to that unit alone. Usually, specific control characters precede the message enabling the selected unit to accept the data that follows.

Advance Pulse or Interval Advance (ADV) — A discrete command issued by the master computer which causes an online controlled unit to change condition, generally advancing the unit to the next position or state.

Advance Ramp Control Warning Sign — Component of an entrance ramp control system which indicates to traffic approaching the ramp that the ramp is being metered.

Agreement (Contract) — The written agreement between the owner and the contractor covering the work to be performed.

Algorithm — A procedure, process, or rule for the solution of a problem in a finite number of steps. An algorithm may be a set of computational rules for the solution of a mathematically expressed problem or for evaluating a function.

Allowable Gap — The time gap between successive moving vehicles at which a greater gap should terminate the green on one phase and transfer right-of-way to another phase.

Alphanumeric Display — Display consisting of letters (ROAD ICY), digits (30), or combinations of both (ROAD ICY, SPEED 30 MPH).

Amplifier (Detector Electronics) — A device that is capable of intensifying the electrical energy produced by a sensor (NEMA). Example is a magnetic-detector amplifier. A loop-detector unit is commonly called an amplifier, although its electronic function actually is different.

Amplitude Modulation (AM) — A method of transmitting information by varying the strength of a carrier waveform in accordance with the instantaneous value of the intelligence-bearing signal.

Analog — An electronic design that uses continuously variable quantities such as voltages, rather than numbers.

Analog Computer System — A control system that uses as analog computer as a master. An analog computer solves problems by operating on continuous variables that represent continuous data. Problems are solved by translating physical conditions (such as numbers, volumes, time, or speed) into related electrical quantities and using electrical circuits as analogs to represent the physical phenomenon. Analog techniques have been used extensively in actuated controllers and arterial systems.

ANSI (American National Standard Institute) — A governmental organization to establish standards replacing the original CODASYL committee, which was dedicated to the development of Common Business Oriented Language (COBOL). ANSI differs in that the scope has been expanded to include standardization of other facets of data processing.

Applications Software — Computer programs which perform control strategy functions and such tasks as basic detector data processing, computing signal transitions from one timing pattern to another, transmitting, information to controls and displays, analyzing equipment operation for malfunctions, and interpreting operator's commands.

Area Detection — The continuous detection of vehicles over a length of roadway wherein the call of a vehicle in the detection area is intended to be held for as long as the vehicle remains in the detection area. (Some detectors are not capable of holding the call indefinitely.) Frequently referred to as "large-area detectors" or "long-loop presence detectors."

Areawide Control — A form of signal system control which treats all of the traffic signals in a city, metropolitan area, or major portion thereof as a total system.

Arithmetic Unit — An electronic unit within a computer CPU which performs arithmetic and logic operations. Most arithmetic units can process an entire word of bits in a single cycle.

Array — (1) An orderly arrangement of things or of representations of things in a visual display (e.g., console or status panel). (2) Data in the form of signs, symbols, alphanumeric characters, etc., arranged so that the relative position of an element of an array has some bearing on the operation that will be performed on the element.

Arterial Intersection Control (Open Network Control) — A form of control for signalized intersections along an arterial street where major consideration is given to the provision of progressive traffic flow along the arterial. The signalized intersections are usually operated as a system.

ASCII (American Standard Code of Information Interchange) — A standard code that assigns special bit patterns to each sign, symbol, numeral, letter, and operation in a specific test. The basic code uses 6-bit characters, allowing 64 (26) different encoded characters.

Assembler — A computer program that prepares a machine language program from a symbolic language (assembly) program by substituting machine language instructions for symbolic instructions.

Assembly Language — A machine-dependent symbolic language which must be converted to machine language before it is usable on a computer.

Asynchronous Data Transmission — A mode of data transmission by which the execution of the next instruction or next event is initiated by a signal that is generated upon completion of the previous command or event.

Attenuation — The loss in signal strength associated with the transmission process. Attenuation is usually expressed as the ratio of received signal strength to transmitted signal strength. This ratio is often expressed in decibles, a logarithmic unit for expressing dimensionless ratios.

Attenuation Distortion — The distortion of a transmitted signal caused by the nonuniform loss or gain at different frequencies.

Attenuator — An electronic circuit element which reduces the strength or magnitude of a signal or action.

Auto Restart — The integration of hardware logic and electrical circuitry with software programming capabilities enabling a computer system to be reactivated without operator intervention, following a power failure.

Auxiliary Equipment — Separate devices used to add supplementary features to a controller assembly.

Auxiliary Storage — A storage device which serves as an extension to processor storage. Data and instructions can be moved by the CPU between auxiliary storage and processor storage.

Available Systems Technology — The present state of the art relative to the ability to readily obtain (purchase and install) a complete traffic control system.

Background Cycle — The term used to identify the cycle length established by a coordination unit and master control in coordinated systems.

Background Processing — The execution of low-priority programs in conjuction with high-priority or real-time processing. Background processing is interrupted as required to accomplish the foreground (high-priority) operations, in real time. (See ***Multiprocessing, Foreground Processing.***)

Backup System — A standby traffic signal control system that can be used to operate a computerized traffic signal system during computer downtime periods for routine maintenance or emergency failure periods. The backup system may be composed of components which, during normal operation, carry out other lower priority tasks or of components which are redundant during normal system operation. (See ***Standby System for Local Operations.***)

Band Speed — The slope of the through-band on a time-space chart.

Bandwidth — (1) The amount of green time available to a platoon of vehicles in a progressive signal system. Also referred to as through band. (2) A range of frequencies that a communications channel will carry without excessive attenuation.

Batch Processing — An offline sequential-processing technique in which a number of similar input items are grouped for processing during the same machine run.

Baud — A unit for expressing the rate at which information is transmitted. A rate of one baud is one useful signal element per second. A bit rate is not necessarily equal to the baud rate in that a signal element may carry more than one bit of information, and some bits may be used for purposes other than carrying signal information.

Benchmark Program — (1) A problem used to evaluate the performance of hardware or software or both. (2) A problem used to evaluate the performance of several computers relative to each other, or a single computer relative to system specifiations.

Benefit-Cost Analysis — Economic study of project alternatives used to determine the comparative worth of each. Based on alternative benefits versus costs usually expressed in dollars.

Bid Proposal — A written document expressing a bidder's intention to perform certain work, in a proposed method, for an expressed amount of money, usually within a certain time frame.

Binary — (1) A characteristic or property involving a selection or condition in which there are two and only two possibilities. Use of a binary system is predicated on the supposition that a duality exists: that is, a thing, state, or condition is or is not. (2) A numbering system based on two which only uses the digits 0 and 1.

Binary Coded Decimal — A means of representing a decimal number by representing each individual digit as a group of bits.

Bit — (1) An abbreviation of ***Binary digit***. (2) A single character in a binary number.

Bit Rate (BR) — The speed at which bits are transmitted, usually expressed in bits per second.

Bits Per Inch (BPI) — Tape packing density on a tape drive. It is the number of bits on one track contained on one inch of tape.

Blocking Factor — The number of data records in a data block. (Also see ***Data Block***.)

Bootstrap — (1) An existing version, perhaps a primitive version, of a computer program that is used to establish another version of the program. (2) A technique or device designed to bring itself into a desired state by means of its own action, e.g., a machine routine whose first few instructions are sufficient to bring the rest of itself into the computer from an input device. (3) That part of a computer program used to establish another version of the computer program. (4) To use a bootstrap.

Bottleneck — Physical or geometric features of a street or freeway which reduce the facility's capacity (or ability to accommodate traffic flow) as compared to other locations on the same facility.

Breakdown — Any event that causes a loss of signal indication to any or all intervals or approaches.

Broad Band Communications — A band of communication frequencies above 4,000 Hertz, usually transmitted over coaxial cables.

Buffer — A device or system used to make two other devices or systems compatible, in particular, (1) a device or routine that compensates for differences in time of occurrence or rates of flow when data is transmitted between devices, or (2) a circuit between two other circuits to prevent undesirable interaction. A second, redundant, usually temporary, area in memory or storage for data.

Bug — A mistake in a computer program.

Bus/Carpool Priority Control — Concept of traffic control which gives preferential treatment to buses and carpools.

Bus Priority — Cycle-by-cycle timing of a traffic signal so the beginning and end times of green may be shifted to minimize delay to approaching buses. The normal sequence of signal displays is usually maintained.

Bypass Lanes on Entrance Ramps — Priority control technique which enables priority vehicles to avoid waiting in queues with nonpriority vehicles on entrance ramps.

Byte — A sequence of adjacent bits used to represent a single character of information. The most common byte sizes are 8 bits and 16 bits.

Cable — A group of separately insulated wires wrapped together.

Call — A registration of a demand for right-of-way by traffic at a controller unit. The call comes to the controller from a detector that is outputting an actuation.

Calling Detector — A detector that is installed in a selected location to detect vehicles which may not otherwise be detected, and whose output may be modified by the controller unit (NEMA). This traditionally has meant a small-area detector near the stop line, to detect vehicles entering the roadway from a nearby driveway during a red or yellow interval. When the signal is green, the detector is disconnected so that extensions of the green can come only from the detector located upstream of the driveway.

Camshaft — The adjustable or selective device used to change signal indications upon activation by the dial unit.

Camshaft Control — A method of computerized control of an electromechanical-type controller. A hold-on-line signal puts the controller under computer control. Advance pulses are then used to operate the stepping motor or solenoid that advances the camshaft to the next interval position. (As contrasted to ***Dial Control***.)

Candidate System — A complete traffic control system (defined in conceptual and functional terms) which can be considered as a feasible choice for implementation.

Capacity — The maximum volume that has a reasonable expection of being accommodated by a roadway component under prevailing conditions, usually expressed as vehicles per hour (vph).

Card Punch — An item of peripheral computer equipment for punching holes into cards which represent data.

Card-Rack-Mounted Detector Units — Units that do not have an individual enclosing case. They are connected by inserting the printed-circuit board into a receptacle mounted within the cabinet. (Compare ***Shelf-Mounted Detector Units***.)

Card Reader — An input device to the computer which transcribes data from punch cards to working storage or magnetic tape.

Carrier Signal — The signal that is used to carry information during data transmission. The characteristics of the carrier signal are changed in accordance with the data that are to be transmitted. (See also ***Modulation***.)

Carryover Output — The ability of a detector to continue its output for a predetermined length of time following an actuation (NEMA). Such a detector is called an extended-call detector or a "stretch" detector. It can be designed to begin the timing of the carryover output when the vehicle enters the detection area, or when it leaves. The latter design is much more common.

Cassette Tape Recorder — A peripheral slow-speed auxiliary device which stores information on an encased magnetic tape.

Cathode Ray Tube (CRT) — An electronic vacuum tube similar to a TV picture tube containing a fluorescent screen on which information or patterns may be displayed.

Central Processing Unit (CPU) — The hardware component of a computing system that contains the circuits that control and perform the execution of instructions. It consists of the control unit(s), arithmetic units(s), and special register groups.

Centralized Control — Form of traffic signal control in which the ability to make control decisions and to issue control commands is placed at one location.

Centralized System — A computer control system in which the master computer, central communication facilities, console, keyboard and display equipment are all situated at a single location. From this center, the operating staff coordinates and controls traffic signals and related traffic control functions throughout the area. (In contrast to ***Distributed System***.)

Channel — Electronic circuitry which functions as a loop detector unit (NEMA).

Character — One symbol of a set of elementary symbols such as those corresponding to the keys on a typewriter. These symbols usually include the decimal digits 0 to 9, the letters A througn Z, punctuation marks, operation symbols and any other single symbols which a computer may read, store, or write.

Check Out — ***See Debug***.

Checkout Detector — Component of an entrance ramp control system which senses the departure of a vehicle past the ramp metering signal.

Chip — See ***Integrated Circuit***.

Circuit — A closed path followed by an electric current.

Closed-Loop Control System — A system capable of controlling some operation by implementing certain strategies, receiving inputs which permit the rapid evaluation of the effects of the control, and then taking some action which modifies the strategy on the basis of the evaluation, all without the need for operator input.

Closed Network Control — A form of control for a group of signalized intersections where relationships from a signal timing viewpoint, must be considered. A typical example is the control of signals in the central business district (CBD) of a city.

Closed Specification — A specification written around a particular item of material or equipment with the intent of limiting bids to one manufacturer.

Coaxial Cable (Coax) — A single central conductor having a common axis with a second outer conductor.

COBOL (Common Business Oriented Language) — A data processing language that resembles business English. Used in business data processing applications characterized by simple arithmetic operations on masses of data.

Command — (1) A signal that initiates a control function. (2) A machine language instruction.

Common Carrier — One of several licensed corporations that offer data transmission services such as speech, television, or digital data transmission. A common carrier is required to supply communication service to all users at published rates.

Communication Error — Any case wherein the data received from a channel do not agree with the data transmitted.

Communication Link — The means of connecting one location to another in order to transmit and receive data.

Communication Network — A composite of communication links.

Communication System — The composite of communication links and associated communications equipment which interconnect all the control and surveillance components of a traffic control system.

Communications — Transfer of information from one location to another so that meaning is understood.

Communications Control Unit (CCU) — The portion of a system that handles the communication processes. The CCU may be a software program or a separate hardware unit. It handles message transmission; errors, control functions, and other communication-related tasks.

Compiler — A computer program that translates a high-level language program to symbolic language.

Computer — See ***Digital Computer***.

Computer Adapter Unit — A device which allows a digital computer to interface a local controller and thereby allow the computer to be in command of the signal indications. (See ***Controller Interface Unit.***)

Computer Control — Regulation and/or supervision of traffic control devices by a computer.

Computer Program — A series of instructions or statements in a form acceptable to the computer which will achieve a certain result.

Concentration — See ***Density***.

Conditioned Line — A communications cable specially compensated to provide improved transmission characteristics.

Conditioning — A common-carrier service whereby the electrical characteristics of a channel are tuned so as to give improved data transmission.

Conditions to Contract — General and special conditions set forth in a written statement which forms part of the contract documents and which prescribes the manner in which a contract is to be carried out.

Conductor — Same as ***Wire***. Used to transmit information (i.e., electrical impulses) between computer and controller as well as within the computer and controller/signal subsystems.

Conflict Monitor — A device used to continually check for the presence of conflicting signal indications and to provide an output in response to conflict.

Congestion — Condition of overcrowding on a roadway caused by demand exceeding capacity, which is manifested by high densities, low volumes, low speeds, stop-and-go driving, increased delay, and high rate of rear-end collisions occurring upstream of the bottleneck.

Congestion Detection — A system of hardware and software designed and operated to provide data on the level of traffic congestion in the area being detected.

Console — A device used for communication between the operator and the computer. A console includes display panels, CRT, some type of hard-copy printer, and a system central panel.

Construction Phase — That part of the project which deals with construction.

Consultant/Contractor Contract — In managing a project, a consultant (engineer) is hired to perform the feasibility study and system design as well as to perform monitoring of contractor activities during installation and/or construction. The contractor is hired separately and is responsible for system installation, checkout, documentation, and training.

Continuous-Presence Mode — Detector output continues if any vehicle (first or last remaining) remains in the field of influence (NEMA). (This definition should not be understood to imply that the use of this mode guarantees that the output will continue for whatever length of time the vehicle remains in the detection area, as some detectors area not capable of holding a call indefinitely.)

Contract Documents — The design plans, technical specifications, bid proposal, bonds, notice of award, addenda, and modifications to the contract.

Contraflow Lane — Priority-control technique, used during peak periods, which provides a priority-vehicle lane on the off-peak side of the median.

Control Area — A grouping of sections. (A section is the smallest grouping of intersections that the computer considers. These intersections are so interdependent or close together that they always work in consort.) Control areas are generally defined by the physical proximity of sections and by the similarity of traffic conditions which permits independent control by the computer within the constraints imposed by required interface between sections and overall system requirements.

Control Center — Consists of the room(s) that contains the computer equipment, displays and controls, and houses the personnel which operate this equipment used in a computerized traffic control system.

Control Interval — Period of time during which signal timing parameters are held constant.

Control Panel — (1) ***System Control Panel***: A panel for operation of the system. (2) A panel on the computer designed for use by the computer operator in communication with the computer

Control Subarea — Subdivision of a single control area. (See ***Section.***)

Control Variables — Traffic condition indicator which are used as the basis for selecting traffic control strategy or tactics.

Controller Assembly — A complete electrical mechanism mounted in a cabinet for controlling the operation of a traffic control signal.

Controller Interface Unit (CIU) — The piece of equipment inserted between the local intersection communication terminal and the intersection controller unit to translate the instructions from the computer into commands that are recognized and responded to by the controller unit.

Controller Unit — The part of the controller assembly which performs the basic timing and logic functions (NEMA).

Conversational Mode — A mode of operation of a data processing system in which a sequence of alternating entries between a user and the system resembles a conversation between two persons.

Coordination — The establishment of a definite timing relationship between adjacent traffic signals.

Coordinator — A device used to relate the timing of one controller unit to others.

Cordon Counts — Number of vehicles crossing a line defining an enclosed area. Both entries and exits from the enclosed area are recorded during selected time periods.

Core — Tiny donut-shaped piece of magnetizable material capable of storing one binary digit. The most common processor storage data representation medium. (Also called ***Magnetic Core.***)

Core Resident — The word ***Resident*** as used here denotes a program or routine which is available in the core memory. Nonresident programs are taken from peripheral storage devices.

Core Storage — See ***Processor Storage.***

Corridor — A freeway and the system of roadways influenced by the freeway which accommodates travel demands between two or more geographical areas.

Corridor Control — Coordinated regulation, warning, and/or guidance of traffic on a system of roadways which accommodate travel demands between two geographical areas.

Corridor Control Strategy — Procedure used to integrate the operation of the various control and driver information systems in a corridor in order to optimize the utilization of corridor capacity.

Critical Intersection Control (CIC) — An algorithm employed to dynamically control the split at signalized locations where the traffic patterns are such that special control, responsive to changing conditions, is needed.

Critical Lane Detection — A system of hardware and software designed to provide data on traffic flow for a selected lane, usually the heaviest volume lane on an approach to a signalized intersection.

Critical Path Method (CPM) — A technique of project management which relates the interdependency of project tasks based on time and cost factors and which ensures a timely and adequate project completion.

Crosstalk — Mutual coupling of magnetic fields, producing interaction between two or more detector units in the same cabinet, when the units are operating the similar frequencies. Crosstalk results in a detector outputting an actuation in the absence of a vehicle.

Cycle — In a pretimed controller unit, a complete sequence of signal indications. In an actuated controller unit, a complete cycle is dependent on the presence of calls on all phases.

Cycle Length — The time period in seconds required for one complete cycle.

Cycle Locking — When cycle lengths of approximately the same length are selected by the computer for two or more sections of the system, one consistent cycle length is selected and imposed on these sections. The sections are then, in effect, locked together on the same cycle length.

Cycle Selection — The process by which cycle lengths are chosen or calculated by the computer to be imposed on the individual sections of the control system.

Data Acquisition — The process by which a computer acquires data from controllers, detectors, and other remote sensors and assembles this raw data for use.

Data Base — The assemblage of data constants and parameters used by computer algorithms in the execution of the traffic control function. Normally included are timing parameters, adjustment coefficients, algorithm coefficients, limit parameters, etc.

Data Base Generator — The program used to assemble a data base prior to the initiation of system operation.

Data Base Updating — The process by which the data base is modified to current value levels.

Data Block — One or more data records stored on an auxiliary storage device in a contiguous block in order to make more efficient use of the storage capacity of the device.

Data Concentrator — A computer-like device that accepts data from a group of low-speed devices and assembles their messages into blocks of data that are transmitted over a single higher-speed linkage.

Data Element — A single unit of data, such as a name or a serial number.

Data Packing — The process of fitting together information which requires less than a full computer word into groups so as to effectively use storage in the computer memory.

Data Record — A group of related data elements treated as a unit in input-output operations.

Data Register — A small capacity (usually one word) data storage area in the CPU.

Data Set — (1) A particular complement of data used for a specific traffic control purpose. (2) A modem which performs modulation, demodulation, and control functions that are necessary to provide compatibility between communications facilities and a computer or remote terminal equipment. (*Data Set* is a registered trademark of the Bell System.)

DC Keying — The process of pulsing with DC a particular remote device or apparatus.

DC Multiplexing — A process involving the use of different voltage levels to represent different channels.

Debug — To detect, locate, and correct mistakes in a computer program. A program that is completely debugged is said to be checked out.

Decentralized Control or Decentralized System — A form of traffic signal control in which the ability to make control decisions and issue control commands is placed at more than one location.

Decibel Random Noise (DBRN) — A measurement of noise power in decibels.

Decoder — A mechanism for translating a code into its various components.

Dedicated Lines — Communication lines used solely to interconnect two or more locations and not normally switched.

Delay — (1) A measure of the time that elapsed between the stimulus and the response. (2) The retardation of the flow of information in a channel for a definite period of time. (3) ***Traffic Delay***: The time lost by vehicle(s) due to traffic friction or control devices.

Delay Distortion — The degradation of a signal transmitted on a communications line that results from differences in the delay experienced by the various frequency components of the signal.

Delayed Output — The ability of a detector to delay its output for a predetermined length of time following the arrival of the vehicle into the zone of detection.

Deliverable Services — Those services associated with the implementation of a control system which relate to system documentation, training, and maintenance.

Delta Clock — The timing mechanism used to measure the elapsed time between two events.

Demand — The need for service, e.g., the number of vehicles desiring to use a given segment of roadway during a specified unit of time.

Demand-Capacity Control — A traffic-responsive, entrance-ramp control strategy whereby metering rates are selected on the basis of a comparison of the freeway demand upstream and the freeway capacity downstream of the entrance ramp.

Demand Control (Loop Occupancy Control) — A detector/controller design using long detection loops (normally 30 ft or longer), with the unit operated in the nonlocking mode. A loop occupancy controller may, but need not necessarily, be designed to rest in all red in the absence of any traffic demand. Loop occupancy control can utilize magnetometer detectors as well as loop detectors.

Demand Operation — A mode of operation in which the service provided at an intersection reflects the presence of demand for that service often without regard for background cycling.

Demodulation — The process of retrieving information from some previously modulated source. The reverse process of modulation.

Demultiplexing — The process of retrieving two or more communication channels from a multiplexed transmission media.

Density — (1) A measure of the number of vehicles per unit length of roadway. (2) The number of bits that can be recorded per inch of magnetic media.

Density Contour — Plotting of density levels on a roadway using distance along the roadway as the x-axis and time of day as the y-axis.

Density Controller Unit — An actuated controller unit that has timing adjustments for the selection of the allowable gap independent of the passage time.

Design Plans — Drawings indicating the manner in which components of a control system are to be constructed and installed.

Detector — A device for indicating the presence or passage of vehicles or pedestrians (NEMA, 1975). This general term is usually supplemented with a modifier, i.e. loop detector, magnetic detector indicating type. Such terminology parallels radio antenna for adding specifies of type. See ***Sensor Detector Unit, Detector System*** and ***Vehicle Detector System***.

Detector Failures — The occurrence of detector malfunctions, including nonoperation, chattering, or other intermittently erroneous counting.

Detector Memory — The retention of an actuation for future utilization by the controller assembly.

Detector Mode — A term used to describe the duration and conditions of the occurrence and conditions of the occurrence of a detection output (NEMA, 1981).

- ***Pulse Mode***: Detector produces a short output pulse when detection occurs. The pulse lasts only about 100 ms, even if the vehicle remains in the detection zone for a longer time.

- ***Controlled Output***: The ability of a detector to produce a pulse that has a predetermined duration regardless of the length of time a vehicle is in the field of influence.

- ***Continuous-Presence Mode***: Detector output continues if any vehicle (first or last remaining) remains in the field of influence. See remarks for Continuous-Presence Mode, above.

- ***Limited-Presence Mode***: Detector output continues for a limited period of time if vehicles remain in field of influence.

Detector System — The complete sensing and indicating group consisting of the detector unit, transmission lines (lead-ins), and sensor.

Detector Setback — Longitudinal distance between stop line and detector. ***Detection Zone***: That area of the roadway within which a vehicle will be detected by a vehicle detector (NEMA). (Also called ***Zone of Detection*** or ***Sensing Zone***.)

Detector Unit — The portion of a detector system other than the sensor and leadin, consisting of an electronics assembly.

Diagnostic — (1) Pertaining to the detection, discovery, and further isolation of a malfunction or mistake. (2) A program that facilitates computer maintenance by detection and isolation of malfunctions or mistakes.

Diagrammatic Sign — Class of sign which combines graphics or symbols with selective alphanumeric displays.

Dial Control — An alternative method of computerized control of an electromechanical type controller. The computer controls the dial motor by issuing a dwell signal. When the dwell signal disappears, the dial restarts and follows the fixed interval pattern (i.e., vehicle change and clearance intervals, pedestrian clearance intevals, leading/lagging greens, etc.), as contrasted with camshaft control. (Same as ***Dial Supervision***.)

Dial Disconnect — The process of interrupting the connection between the dialpulsing circuit and the signal camshaft rotational device in some types of intersection controllers.

Dial Supervision — The technique for allowing the dial to dwell for an adjustable period of time in one or more of the intervals comprising the cycle. This permits the computer to independently extend the duration of each phase beyond its preset minimum. (Same as ***Dial Control***.)

Dial Unit — Consists of a dial graduated in one percent increments from 0 to 100 percent. Timing keys placed in the dial unit are used to affect changes in signal indications.

Dibits — A group of two bits.

Digital Computer — A device capable of accepting information, applying prescribed processes to the information, and supplying the results of these processes. It usually consists of input and output devices; storage, arithmetic and logic units; and a control unit.

Digital Traffic Control Computer System — A control system that uses a digital computer to control traffic signal controllers.

Digital Logic — (1) Logic related to numbers through the use of arithmetic and logic processes. (2) Hardware to effect these processes.

Dilemma Zone — A distance or time interval related to the onset of the yellow interval. Originally the term was used to describe that portion of the roadway in advance of the intersection within which a driver can neither stop prior to the stop line nor clear the intersection before conflicting traffic is released. That usage pertained to insufficient length of timing of the yellow and/or red clearance intervals. More recently the term has been used also to describe that portion of the roadway in advance of the intersection within which a driver is indecisive regarding stopping or clearing, although the signal timing is long enough to permit either. That portion of the roadway in advance of the intersection within which a driver is indecisive regarding stopping prior to the stop line or proceeding into or through the intersection. May also be expressed as the increment of time corresponding to the dilemma zone distance. ***Dilemma Zone Protection***: Any method of attempting to control the end of the green interval so that no vehicle will be in the dilemma zone when the signal turns yellow, or delay the onset of an opposing green indication if a vehicle is in the dilemma zone.

Direct Access — Data in storage can be read and written without processing the data which precede it on the storage device. The time required for data access is effectively independent of the location of the data. Disks and drums are direct access devices. (Also see ***Random Access***.)

Direct Addressing — An immediate and explicit indication of the referenced location. It is usually a part of the computer instruction specifying the location of the operand or the location of another instruction. (In contrast, see ***Indirect Addressing***.)

Direct Memory Access (DMA) — A method used in computerized systems to allow high-speed peripheral equipment to obtain stored data on a cycle-stealing basis. This allows simultaneous processing and input/output data transfer.

Direct Wire — A communiations method which uses wire interconnect between the transmission and reception points with no multiplexing. (See ***Dedicated Line***.)

Directional Detector — A detector capable of being actuated only by vehicles traveling in one direction.

Disc — The circular-shaped device used in the production of some changeable-message-sign legends. It may be retro-reflective or [illegible]lar.

Disk — A peripheral device used in computer systems to provide large volumes of storage which is available to the computer in blocks with an access time delay on the order of 100 milliseconds. Also called ***Magnetic Disk***. (See ***Fixed Head Disk***, ***Moving Head Disk***.)

Disk File — A segment or block of disk memory separated for storage of particular information.

Display Map — A graphic display of the street system being controlled showing the status of the signal indications and possibly the status of traffic flow conditions.

Distributed System — A control system in which individual computers are installed in each of the major control areas of a total system, and a supervising master is used to provide interface between the individual areas and to make decisions on timing patterns affecting two or more areas. (In contrast, see ***Centralized System.***)

Diversion — An aspect of corridor control which refers to the directing of traffic from corridor links with excess demand to those with excess capacity.

Diverted Traffic — Vehicles which choose not to use the freeway at all, or else to enter it from another location or at another time instead of waiting to enter at a particular entrance ramp. Also refers to drivers that choose to use another mode of transportation (e.g., carpools or public transit) instead of driving on the freeway.

Doppler Effect — A change in the frequency with which waves from a given source reach an observer, when the source and the observer are in rapid motion with respect to each other, by which the frequency increases or decreases according to the speed at which the distance is decreasing or increasing.

Double Alternate — A signal timing plan where two adjacent signalized intersections have the same offset and a half-cycle offset occurs between pairs of signalized intersections.

Downstream — The roadway extending, from a reference point, in the direction of the traffic movement that is being discussed.

Down Time — The time during which a device is unavailable for normal operation.

Down Time Accumulator — A clocking mechanism activated during the interval when a device is inoperable. It provides a measure of the cumulative total elapsed downtime. Usually used to determine the length of a power outage.

Drift — Change in the electrical properties of the detector system or a portion of it due to environmental changes, particularly temperature variations and rain water.

Driver Information System — Concept of traffic control which advises motorists of prevailing traffic conditions and, in some cases, provides recommendations as to the best routes to travel.

Drop Procedures — (1) The orderly processes or operations to remove a controller from the control of the computer. (2) The process followed at the local intersection when a communications failure occurs.

Dual-Ring Controller Unit — A dual-ring controller unit contains two interlocked rings which are arranged to time in a preferred sequence and to allow concurrent timing of both rings.

Dump Programs — Software used to output specified areas of storage which is useful in dubugging computer programs and system diagnosis.

Dummy Interval — A redundant interval in the cam switching mechanism incorporated to allow the total number of intervals in the cycle to correspond integrally with the total number of intervals provided on the cam switching mechanism.

Duplex — Two-way communication on a single communication channel. (See ***Half Duplex***, ***Full Duplex***.)

Dynamic Split Adjustment — The process or computer program used to vary the split among the various phases of a cycle in real time in accordance with the conditions to be satisfied. (Same as ***CIC***.)

EARPROM (Electrically Alterable Programmable Read-Only Memory) — See ***Electrically Erasable Programmable Read-Only Memory (EEPROM)***.

Echo Distortion — The distortion caused by an impedance mismatch or by a sudden change in the properties of a line which results in an echo or reflected wave which lowers the quality of the transmitted signal by distorting the shape of the wave.

Editing Capability — See ***Electrically Erasable Programmable Read-Only Memory***.

EIA-RS232 Interface — The standard interface between data terminal equipment and data communication equipment employing serial binary data interchange. Restricted to 50 ft and relatively slow speed.

Electrically Erasable Programmable Read-Only Memory (EEPROM) — An electrically erasable PROM. The contents of this device are modified through the application of an electrical voltage that is higher than that voltages that are applied by the microprocessor during normal operation. Also designated as the ***Electrically Alterable PROM***, ***EARPROM***.

Electromagnetic — Produced by electromagnetism. Consists of magnetic material surrounded by a coil of wire through which an electric current is passed to magnetize the material.

Electromechanical Controller Unit — A controller unit which performs its functions on the basis that an electrical impulse causes a mechanical action to take place.

Emergency Repairs — All work required to restore a signal installation, or system, to its original state after a service failure.

Emergency Vehicle Preemption — The transfer of the normal control of signals to a special signal control mode for emergency vehicles.

Encoder — (1) A device which converts data into a form for transmission over the communication link between two points in a system. (2) A circuit to transform data from one form to another, e.g., convert discrete decimal characters into binary characters. (3) A system which converts signals which have been fed into the system individually into combinations of outputs.

Entrance Ramp Control — Regulation of the number of vehicles per unit time entering a freeway so that the demand on the freeway itself does not exceed the capacity; and/or the guidance of vehicles entering a freeway into gaps in the freeway traffic stream, in order to improve the safety and capacity of the merging operation.

Envelope Delay — (1) ***Absolute Envelope Delay*** refers to the amount of delay encountered by the modulating energy in a signal between the sending and receiving end of any circuit. (2) ***Relative Envelope Delay*** is a difference in delay at various frequencies but with a specific frequency selected as a reference point for all other frequencies.

Epitaxy — Process of placing material on a surface. Used to grow thin layers of silicon on a base material to produce integrated circuits and transistors.

420

Equipment Status Monitoring — The ability to determine the operational characteristics of a remote device in terms of "operating normally," "malfunction," "communications errors," etc.

Erasable Programmable Read-Only Memory (EPROM) — A device that stores data which can be altered through the use of a special device.

Error — Any case wherein the data received from a channel do not agree with the data transmitted.

Error Correction — The process by which sufficient redundant or check information is included with data that are transmitted so that the receiver can, within certain ranges of error, reconstruct the correct message from a message that is received in error.

Error Detection — Similar to error correction except that check information is used only to identify erroneously received data, and no correction is made. Requires far less redundancy and check information.

Error Rate — The expected frequency of transmission errors over a channel, usually expressed as the ratio of bits-in-error to total bits transmitted. One error per 100,000 bits transmitted gives an error rate of 10-5.

Executed Cycle — The portion of a CPU's operational cycle during which the decoded instruction is executed.

Executive Routine — A supervisory program used to control the processing of specific programs.

Exit Ramp Closure — Type of exit ramp control which allows no vehicles to leave the freeway at a particular egress or exit point.

Exit Ramp Control — Regulation of traffic flow leaving a freeway at a point of egress or exit.

Exit Ramp Metering — Restriction of traffic flow leaving a freeway at a point of egress or exit.

Expansion Wave — Boundary, moving downstream of an incident, between the region of traffic flow affected by the incident and that region of traffic flow not affected by the incident.

Extended Binary Coded Decimal Interchange Code (EBCDIC) — An 8-bit representation of original 6-bit BCD codes.

Extended Call Detector — A detector with carryover output. It holds or stretches the call of a vehicle for a period of seconds that has been set on an adjustable timer incorporated into the detector. It can be designed to begin the timing of that period when the vehicle enters the detection area, or when it leaves. (See ***Stretch Detector***.)

Extension Detector — A detector that is arranged to register actuations at the controller only during the green interval for that approach so as to extend the green time of the actuating vehicles (NEMA).

Extension Unit — The timing interval during the extensible portion which is resettable by each detector actuation. The green interval of the phase may terminate on expiration of the unit extension time.

Failsafe (as in output relay design) — A type of output-relay design that produces a constant call, thereby keeping traffic moving, in the event that the detector unit loses power.

Fetch — The procedure by which one or more bytes of data are located, then transferred from processor storage to the CPU.

Fiber Optics — Technique for the transmission of light from a high-intensity, low-voltage lamp through a bundle of tiny and flexible glass fibers.

Filtering Equation — An equation used to smooth discrete data and determine the average trend of the data. The equation is used in an iterative process to determine smoothed data points. (Also see ***Smoothed Data Value***.).

Firmware — Memory and its contents that cannot be changed readily.

First-Generation Control (1-GC) — This type of control is based on a table lookup approach. A number of fixed timing plans have been precomputed and stored. Timing plans are selected based on sensing certain demand parameters at strategically located detectors. As thresholds are reached, predeveloped and stored timing plans are implemented. This procedure is used in most of the presently operational digital computer controlled systems.

Fixed Delay — Time loss caused by traffic control devices (e.g., signals, stop signs, railroad crossings) which occurs regardless of the amount of traffic volume and interference present.

Fixed-Head Disk — A magnetic disk system in which read/write head is permanently positioned over a given track on the disk.

Fixed-Time Controller Assembly — See ***Pretimed Controller Assembly***.

Fixed-Tuned Loop — Describes a loop-detector unit whose output frequency must be adjusted manually to affect detection.

Flip Flop — Temporary storage of one bit.

Flowchart — A graphical representation showing the interconnect sequential logical steps required for the definition, analysis, or solution of a problem. Used to describe a process by displaying its functions in the order and priority of flow.

Force-Off Command (FO) — A system command that forces the termination of the right-of-way.

Forced Flow — The zone of traffic flow at which flows are below capacity and storage areas consisting of queues of vehicles form. Speeds are reduced substantially, and stoppages may occur for short or long periods of time. Normal operation is not achieved until the storage queue is dissipated.

Foreground Processing — A term describing the higher priority tasks to be processed in a multilevel computer processing environment. (See ***Multiprocessing***, ***Background Processing***.)

FORTRAN (Formula Translation) — A high-level, procedure-oriented, computer programming language. Used for scientific applications characterized by lengthy, intricate computations.

Free Flow — The zone of traffic at which there is little or no restriction in maneuver ability due to the presence of other vehicles. Drivers can maintain their desired speeds with little or no delay.

Freeway — Divided roadway with more than one lane in each direction, with grade separations at cross streets, and with access and egress limited to specially designed locations.

Freeway Surveillance — Process or method of monitoring freeway traffic performance and control system operation.

Freeway Traffic Control Concept — Idea which expresses the objective, principle of operation, control variables, and functional components of a freeway traffic control system.

Frequency — (1) The number of oscillations of a signal per unit of time: usually expressed in cycles per second (cps). (2) The number of times an event (i.e., accident, vehicle stop, etc.) occurs per unit of time.

Frequency Division Multiplexing (FDM) — Involves the use of different frequencies (tones) to represent different channels. On a typical telephone circuit of voice-grade quality (Series 3000), up to 16 different tones representing 16 different channels can be transmitted.

Frequency Modulation (FM) — A method of data transmission whereby the frequency of a sinusoidal waveform (carrier) is changed in accordance with the information that is to be carried.

Frequency Response — The plot of frequency versus the ratio of output to input signal for a conductor.

Frequency Shift Keying (FSK) — A form of frequency modulation, typically with marking signals represented by one frequency and spacing signals represented by another frequency. The transmitter is changed from one frequency to another, i.e., keyed to represent a different information character.

Full-Traffic-Actuated Controller Assembly — A type of traffic-actuated controller assembly in which means are provided for traffic actuation on all approaches to an intersection.

Full Duplex — A communication facility providing simultaneous transmission and reception in both directions.

Functional Specifications — Those specifications which describe only ***what*** a system is to do and not ***how*** it is done.

Gamma Correction — A feature installed on a special circuit in a CCTV camera which expands or increases the ratio between bright and dark objects.

Gap-Acceptance Merge Control — Concept of entrance ramp metering which releases and/or guides ramp vehicles into acceptables gaps in the freeway traffic stream by stopping them at a ramp metering signal and then releasing them, usually one at a time, at a time calculated in accordance with the predicted arrival of an acceptable gap at the nose of ramp.

Gap-Out — Termination of a green interval due to an excessive time interval between the actuations of vehicles arriving on the green, so as to serve a conflicting phase.

Gap-Reduction — A feature whereby the allowed time spacing between successive vehicles on the phase displaying the green during the extensible portion is reduced.

Gap/Speed Detector — Component of a merge control system which measures gap sizes and vehicle speeds in the right lane of the freeway.

General Conditions — That portion of the contract documents which relates to general requirements for execution of a contract, work, supervision of work, public safety, payment, etc.

Generation (First, Second, Third) — Denotes significantly different approaches in control philosophies for computerized traffic signal systems. ***First Generation***: Uses prestored timing plans developed offline based on previously collected traffic data. Timing plans can be selected on a basis of time-of-day, operator selection, or automatic matching of the timing plan best suited for existing traffic pattern conditions. ***Second Generation***: Contains an online optimization process to develop the timing plans in real time based upon current traffic conditions. ***Third Generation***: Deals with individual intersections on a cycle-by-cycle basis using an areawide optimization criteria.

Global Variable — A variable applying to the total system.

Goal — Broad statement which expresses long-range overall desires, policies, and positions. (See ***Objective***.)

Government-Furnished Equipment (GFE) — Equipment relevant to a job which is supplied by the governmental body letting the contract.

Green Extension System — Hardware assembly of extended call detectors and auxiliary logic. The logic can monitor the signal display, enable or disable the selected extended call detectors, and hold the controller in artery green.

Green Control — A scheme for controlling an intersection controller assembly whereby a control circuit causes the controller unit to dwell in green intervals until released by the master control unit. Minimum green times and all fixed intervals are timed by the local controller; offset, split, and cycle length are controlled by the master controller.

Guard Band — A region of unused frequencies that separates the different frequency regions assigned within a transmission system. The guard bands facilitate the separation of the signals. (See also ***Frequency Multiplexing***.)

Half Duplex — A communication facility providing both transmission and reception in both directions, but not simultaneously. (See ***Full Duplex***.)

Hard Copy — Data permanently recorded on paper, film, etc., for later reference.

Hardware — The physical equipment in a computer system. (In contrast, see ***Software***.)

Hard-Wired Conflict Monitor — Electrical wiring or circuit in a local controller assembly which acts to prevent certain combinations of signal indications which could result in direct traffic conflicts.

Headway — Time or distance spacing between two successive vehicles in a given traffic lane measured front to front.

Hertz (Hz) — A measure of frequency or bandwidth. One Hertz (Hz) is defined as one cycle per second (cps).

Hierarchical System — A system having various levels of priority or preference.

High-Level Language — A computer programming language using familiar notation, such as English or mathematics, which is easy for the programmer to understand. A high-level language statement will usually generate several machine language instructions.

Hold-On-Line Signal (HOL) — A signal to an intersection controller commanding it to remain under computer control.

Hold — A command that retains the existing right-of-way. A command to the controller unit which causes it to retain the existing green interval.

Hysteresis — A lagging in the return of values to their previous levels, as if from internal friction. Used to describe the delay in recovery of traffic service rate following breakdown due to congestion.

ILD — Inductive loop detector. See ***Loop Detector Unit***.

Impulse Noise — Voltage spikes which are impressed on a line or circuit as a result of momentary voltage surges.

Incident — A noncollision occurrence in a traffic stream which causes a disturbances in the normal flow of traffic. Common incidents include stalled vehicles, spilled loads, near-collisions, etc. Collision accidents are sometimes included in the incident category.

Incident Detection — The arrangement of detectors and processing of detector information to arrive at the decision that some type of incident has probably occurred in the traffic stream. May also be done by visual and third-party reporting means.

Indemnification — The act of being secured against hurt, loss, or damage.

Indexing — The method of retrieving data elements from arrays. (See ***Array***.)

Indirect Addressing — A method of computer cross reference in which one memory location register, or operand indicates the correct address of the intended location. (In contrast, see ***Direct Addressing***.)

Inductance — That property of an electric circuit or of two neighboring circuits whereby an electromotive force is generated in one circuit by a change of current in itself or in the other. The ratio of the electromotive force to the rate of change of the current.

Input — The introduction of data from an external storage medium into a computer's internal storage unit.

Input/Output (I/O) — A general term for equipment used to communicate with a computer.

Input-Output study — Determination of the number of vehicles moving into, out of, or being accumulated in a closed system over a given time period.

Instruction — A set of characters used to define a basic computer operation. An instruction has two basic parts: an ***Operand code*** which specifies the operation to be performed and ***Operand*** or an ***Operand address*** which specifies the data or the address of the data to be operated on.

Instruction Repertoire — The set of instructions which the CPU is capable of performing.

Instruction Set — The complete repertoire of instructions which a CPU is capable of performing.

Instructions to Bidders — Written instructions to bidders on requirements for preparation of a bid.

Integrated Circuit (IC) — An electronic circuit containing many interconnected circuit elements formed on a single body, or chip, of semiconductor material.

Interconnect — The communication media usually consisting of electrical cable connecting the system master with local controllers.

Interconnected Signal System — A number of intersections which are connected by wire, radio, or some other means to effect traffic progression.

Interface — A common boundary at which two separate systems or portions of each join or interact. An interface can be mechanical, as in adjoining hardware surfaces, or it can be electrical, as in signal level transformation points. Moreover, it can also refer to human and machine interface and interaction between the operator and the computer.

Internal Storage — See ***Processor Storage***.

Interrecord Gap (IRG) — A length of unused tape between two data records on a magnetic tape.

Interrupts — A break in the normal flow of a system or routine such that the flow can be resumed from that point at a later time.

Intersection — The common area of roadways that meet or cross.

Intersection Status — (1) The knowledge of whether a controlled intersection is online or operating in its standby mode. (2) In some systems, the knowledge of whether the intersection is displaying Main Street Green or not. (3) In other systems, the knowledge of the specific interval in which the camshaft is positioned or the particular indication is being displayed.

Interval — A part or parts of the signal cycle during which the signal indications do not change.

Interval Sequence — The order of appearance of signal indications during successive intervals of a cycle.

Interval Timing — The passage of time which occurs during an interval.

Invitation for Bid (IFB) — In selecting the contractor for system installation, it is required that an invitation for bid be released and that all qualified contractors be permitted to submit proposals. The IFB process then requires that the local agency select the contractor who has submitted the lowest and best bid.

Isolated Controller Assembly — A controller assembly for operating traffic signals not under master supervision.

Isolated Intersection Control — Form of signal control for a single signalized intersection through which the flow of traffic is controlled without giving any consideration to the operation of adjacent signalized intersections.

Jam Density — Density at which congestion on a roadway causes traffic flow to stop.

Jump Instruction — A computer instruction whose execution causes the address portion of the instruction to overlay the content of the location counter. This causes a departure from the normal sequence of executing instructions. (Also called a ***Branch Instruction*** or a ***Transfer Instruction***.)

KHz — Kilohertz, or thousands of hertz. Hertz means cycles per second, a measure of frequency.

Keyboard — An array of keys which, when depressed, cause the generation of a specific character or symbol in electrical, printed, or other form. Used in conjuction with appropriate gating elements, the keyboard permits the generation of coded symbols for interpretation by, or storage in, the computer. Thus, the keyboard may be part of a manual input device for a computer, a keypunch, a CRT, a paper tape perforator, or part of an electric typewriter.

Kinetic Energy — Relative to a traffic stream, kinetic energy is the product of volume and speed (or the product of density and the square of the speed). Usually expressed in terms of vehicle-miles per hour (vmh).

L — The symbol frequently used for inductance. The symbol "delta L" (Δ L) is used for the change in inductance.

Lamp-Matrix Sign — Sign made up of a matrix of lamps. By selectively illuminating a given set of lamps in the matrix, it is possible to provide an alphanumeric display.

Lane Closure — A concept of mainline control which prohibits travel on particular lanes of a freeway.

Lane Occupancy — A measurement of vehicle presence within a zone of detection, usually expressed as the percent of time a given point or area is occupied by a vehicle.

Language — A set of representations, conventions, and rules used to convey information.

Language Translator — A computer program used to translate a source language program into a machine language program.

Large Scale Integration (LSI) — In integrated circuitry, a silicon chip with more than 1,000 logic elements. (Also see ***Integrated Circuit*** and ***Logic Element***.)

Last Car Passage — A selected feature of a volume-density controller unit which, upon gap-out or max-out, will cause the timing of a full extension unit rather than the reduced gap time before terminating the green interval. The last vehicle to have been detected, known as the ***Last Car***, will therefore retain the green until it reaches the stop line. Thus, it is assured of avoiding the dilemma zone problem and of clearing the intersection. ***Lead-In Cable***: The electrical cable which serves to connect the lead-in wire to the input of the loop detector unit (NEMA). (Sometimes called a ***Home-Run Cable*** or ***Transmission Line***.)

Lead-In Wire — That portion of the loop wire between the physical edge of the loop to the splice box; for a magnetic detector and magnetometer it is the wire which runs from the sensor (probe) to the splice box.

Latent Demand — Total number of potential users desiring to use a facility (street or freeway) at a given point.

Level of Service — Denotes any one of an infinite number of differing combinations of operating conditions that may occur on a given lane or roadway when it is accommodating various traffic volumes. It is a qualitative measure of the effect of a number of factors including speed, travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs. In practice, selected specific levels are defined in terms of particular limiting values of certain of these factors.

Level One Programs — Programs which have a priority level of ***One***, usually the highest priority.

Level One Routines — See ***Level One Programs***.

Light-Emitting Diode (LED) — A solid state device with illumination properties similar to that of a low power incandescent lamp.

Line Adapter — Another term for a ***Modem***.

Line Printer — A printer in which an entire line of characters is printed at once. Line printers are used to print large volumes of information as well as specific formatted reports and other data developed during the operation of the computer control system.

Link — (1) ***Computer***: A process to gather or write two or more separately written, assembled, or compiled programs or routines into single operational entities. Some computer systems have special programs called linkage editors to connect address components into symbols or to perform relocation to avoid overlapping. (2) ***Traffic***: The length of roadway between two signalized locations. (3) ***Communications***: Another term for Channel.

Listing — (1) ***FORTRAN***: A listing of the source program(s) which reflect the compu tational processes. (2) ***Assembly Language***: An optional binary-output program of the compiler. The listing contains the symbolic instructions equivalent to the binary-code output of the assembler. This assembly-output listing is useful as a debugging aid.

Loader — A user-assistance software program which loads the object program into memory for execution. The loader also links subroutines and manages overlay modules.

Loading Coil — A number of turns of wire used for electromagnetic effect or for providing electrical resistance. Used for tuning or matching electronic circuits.

Locking Detection Memory — A selectable feature of the circuit design for a controller phase whereby the call of a vehicle arriving on the red (or yellow) is remembered or held by the controller after the vehicle leaves the detection area until it has been satisfied by the display of a green interval to that phase.

Local Controller Assembly — A controller assembly supervising the operation of traffic signals at a single intersection. (Also see ***Controller Assembly and Controller Unit***.)

Local Variable — A variable whose name is known only to the subprogram to which it belongs. Also refers to a variable parameter which is intersection specific.

Logic Element — The smallest building block in a computer that can be represented by a logical operation in an appropriate system of symbolic logic.

Loop — A sequence of computer instructions that is executed repeatedly until a terminal condition prevails.

Loop Detector — A detector that senses a change in inductance of its inductive loop sensor by the passage or presence of a vehicle near the sensor. (See ***Loop Detector System***.)

Loop Detector System — A vehicle detector system that senses a decrease in inductance of its sensor loop(s) during the passage or presence of a vehicle in the zone of detection of the sensor loop(s) (NEMA). means the same as loop detector but is clearer in its inclusion of the wire as well as the electronics package.

Loop Detector Unit — An electronic device which is capable of energizing the sensor loop(s), of monitoring the sensor loop(s) inductance and of responding to a predetermined decrease in inductance with an output which indicates the passage or presence of vehicles in the zone of detection (NEMA). It is the electronics package, exclusive of the loop(s) and lead-in wire.

Loop Occupancy Control — A detector/controller unit design using long detection loop(s) (normally 30 ft or longer), and a controller unit operated in the non-locking mode. A loop occupancy controller unit may, but need not necessarily, be designed to rest in all red in the absence of any traffic demand.

Loop System — A combination of loops of wire connected through transmission lines (lead-ins) to the detector in-put terminals.

Low-Level Language — A computer programming language that is closely related to machine language. A low-level language statement will usually generate a single machine language instruction.

Low-Power Radio — Noncommercial radio utilized for driver communication.

Machine Independent — A term used to indicate that a source program written for a particular computer can also be translated for and executed on most other computers.

Machine Language — (1) A set of symbols, characters, or signs, and the rules for combining them, that conveys instructions or information to a computer. (2) A language that can be directly interpreted by the control section of the machine. (3) Information or data expressed in code that can be read directly, used, or written by the computer or peripheral machines without further processing. (See ***Assembly Language***, ***Compiler Language***.)

Magnetic Detector — A detector that senses changes in the earth's magnetic field caused by the movement of a vehicle near its sensor (NEMA). A vehicle detector embedded in the roadway which makes use of both the earth's magnetic field and the energy change created by the passage of a vehicle over the detector to produce an output. Not to be confused with a magnetometer detector.

Magnetic Gradient Vehicle Detector (MGVD) — A device which uses a magnetic principle to detect vehicles.

Magnetic Tape — A tape with a magnetic surface on which data can be stored by selective polarization of portions of the surface.

Magnetic Tape Unit — A computer peripheral device which is used to transmit data to and from a magnetic tape. (Same as ***Tape Drive***.)

Magnetometer — A detector that measure the difference in the level of the earth's magnetic forces caused by the passage or prsence of a vehicle near its sensor (NEMA). A device capable of being activated by the magnetic disturbance caused by the passage or presence of a vehicle. A magnetic flux generator/sensor is installed in the roadway and connected to sensor amplifier electronics. (Not to be confused with a magnetic detector.)

Main Frame — The main part of the computer, i.e., the arithmetic or logic unit. (See ***Central Processor Unit***.)

Mainline — The freeway proper as distinguished from the entrance ramps, exits ramps, and interchange geometry of the freeway.

Mainline Control — Regulation, warning, or guidance of traffic on the mainline of a freeway.

Mainline Metering — Concept of mainline control which restricts traffic flow on a freeway.

Maintenance Level — An indicator of system condition expressed in terms of hours of maintenance per year.

Maintenance Rate of Increase — An indicator of system condition expressed as maintenance time per intersection averaged over some time period, usually a year.

Major Street Green (MSG) — Data sent from the intersection controller to the computer indicating that the controller is displaying a green signal to the main traffic phase. Commonly refered to as ***A-phase Green*** and ***AΦG***.

Malfunction — Any event that impairs the operation of a control system without losing the display and sequencing of signal indications to all approaching traffic.

Man-Machine Interface — A device, usually combination of a CRT, teletype, or control panel, which allows the system operator to communicate with the computer system. In some cases, a specialized language is termed a ***Man-Machine Interface*** because of its ability to simplify the conversion between the system and its operator.

Manifest Demand — The number of users observed to use (or actually using) a facility (street or freeway at a given point.

Manual Intervention — The ability of the system operator to manually select certain system operations.

Manual Pattern Selection (MAN) — Signal timing plans selected manually by the operation of a computerized traffic control system. Manual selection is higher priority than all other modes of plan selection.

Map Display — A device which graphically portrays the geometric representation of the system of streets under control. Indicator lights are placed at or near the signalized intersections which may display various information provided by the computer system.

MARK — One state in a 2-state system. The other state is commonly called SPACE. The MARK condition generally represents the TRUE or ON state.

Mass Storage — A memory device capable of retaining large amounts of data (See ***Disk***, ***Magnetic Tape Unit***.)

Master Controller Assembly — A controller assembly for supervising multiple secondary controller assemblies and/or multiple submaster controller assemblies.

Master-Secondary Controller Assembly — A controller assembly operating traffic signals and providing supervision of other secondary controller assemblies.

Maximum Green — In actuated controllers, the longest time for which a green indication will be displayed in the presence of a call on an opposing phase.

Maximum Limit — The maximum green time after an opposing actuation, which may start in the initial portion.

Mean Time Between Failures (MTFB) — The average length of time for which the system, or a component of the system, works without fault.

Mean Time to Repair (MTTR) — When the system or a component of the system develops a fault, this is the average time it takes to correct the fault.

Mean Velocity Gradient — Computed acceleration noise divided by the mean speed.

Measures of Effectiveness (MOE's) — All quantities derived from detector data often used to estimate the effectiveness of the system in improving traffic flow. Common bases of comparison include volume, occupancy, speed, stops, delay, and queue length.

Medium Scale Integretion (MSI) — In integrated circuitry, a silicon chip with between 100 and 1,000 logic elements. (Also see ***Integrated Circuit and Logic Element***.)

Memory — (1) ***Detector Memory***: The retention of an actuation for future utilization by the controller unit assembly. The phrase might better be detection memory to make it clearer that the memory is within the controller, not the detector. (2) ***Nonlocking Memory***: A mode of actuated-controller unit operation which does not require memory (NEMA). In this mode of operation the call of a vehicle arriving on the red (or yellow) is forgotten or dropped by the controller as soon as the vehicle leaves the detection area.

Memory Chip — An integrated circuit used for memory.

Memory Cycle Time — The interval between the call for, and the delivery of, information from a computer central memory. (See ***Access Time***.)

Memory Off — A selectable feature of an actuated controller, synonymous with nonlocking detection memory.

Memory Protect — Computer hardware which will prevent the accidental or deliberate destruction of certain part of memory.

Merge Control — Concept of entrance ramp metering which guides ramp vehicles into acceptable gaps in the freeway traffic stream.

Merge Detector — Component of an entrance ramp control system which senses the presense of a vehicle in the merge area of the ramp.

Metering — Traffic control method or technique for restricting traffic flow.

Metering Rate — Number of vehicles allowed to enter a given section of a roadway per unit time.

Microcomputer — A programmable computer whose CPU is a microprocessor.

Microprogramming — (1) The technique of using a certain special set of computer instructions that consist only of basic elemental operations which the programmer can combine into higher-level instructions as he chooses, and can then program using only the higher level instruction. (2) Machine language coding in which the coder builds his own machine instructions from the primitive basic instructions built into the hardware.

Microprocessing Unit (MPU) — The processor chip used in any microprocessor.

Microprocessor — Microprocessors are basically microminiaturized CPU's. Smaller, slower, less flexible, and less costly than other CPU's.

Microsecond — One millionth of a second.

Millisecond — One thousandth of a second.

Minimum Acceptable Gap — Smallest time headway between successive vehicles in a traffic stream into which another vehicle is willing, and able, to merge.

Minimum Green Interval — The shortest green time of a phase. If a time setting control is designated as "minimum green," the green time shall be not less than that setting.

Mnemonic Symbol — A symbol chosen to assist the human memory, e.g., an abbreviation such a "mpy" for "multiply."

Modem (Modulator Demodulator) — A device used at both ends of a communication channel to transmit and receive data at high speed.

Modulation — The process whereby information is superimposed on another signal for the purpose of transmitting the information over a communications link. The desired information is retrieved by a demodulation process.

Module — (1) ***Software***: A program unit is that is discrete and identifiable with respect to compiling, combining with other units, and loading, e.g., the input to, or output from, and assembler, compiler, linkage editor, or executive routine. (2) ***Hardware***: An assembly of electronic or other equipment mounted in a single enclosure.

Monitor — A device that verifies the operations of a data processing system and indicates any significant departure from the norm.

Moving Head Disk — A mass storage device using a sensing head which moves over the storage medium in much the same way that a phonographic tone arm moves over a record.

Multidrop Connection — The connection of more than two data receiver/transmitter stations to a single communications link. Special control signals must then be used to allow communication between the proper units. A multidrop connection is similar to a telephone party line. (See, also, ***Point-To-Point Connection***.)

Multilevel Control — Form of traffic signal control which utilizes a hierarchical arrangement of control units.

Multiplexed DC — A multiplex method which uses a combination of DC voltage amplitudes to transmit or receive messages.

Multiple Processor Configuration — Multicomputer control system consisting of two or more central processing units. Each CPU can perform a particular set of functions or can control part of the traffic signal system.

Multiplexer (MUX) — A device which uses several communication channels at the same time, transmits and receives messages and controls the communications lines. This device may or may not be a stored program computer.

Multipoint Channels — Communications links (cable runs) which are wired in paralled at multiple sending/receiving stations. Every message to or from any incorporated sending/receiving station is transmitted over the same cable pair.

Multiprocessing — Ability of computer operating system to process more than one programmed task at the same time. (See ***Foreground Processing***, ***Background Processing***.)

Multiprocessor — (1) A control configuration in which more than one CPU is used. (2) A computer with multiple arithmetic and logic units which can be programmed to run more than one task simultaneously.

Multiprogramming — A situation wherein two or more programs are simultaneously competing for the resources of the CPU.

Nanosecond — One billionth of a second.

NETSIM — A simulation program originally called UTCS-1.

Noise — Random variations of one or more characteristics of any entity such as voltage, current, and data. Generally, any disturbance tending to interfere with the normal operation of a device or system.

Noncongested — Absence of congestion, which is sometime arbitrarily defined as a function of traffic variables such as volume, speed, and density.

Nondirectional Detector — A detector capable of being actuated by vehicles traveling in either direction.

Nonlocking Detection Memory — A selectable feature of the circuit design for a controller phase whereby the call of a vehicle arriving on the red (or yellow) is forgotten or dropped by the controller unit as soon as the vehicle leaves the detection area.

Nonlocking Memory — A mode of actuated-controller-unit operation which does not require detector memory.

Nonrecurrent Congestion — Type of congestion resulting from the occurrence of random or unpredictable events.

Notice of Award — The written notice to the contractor by the owner that the contractor is the successful bidder and that, upon compliance with certain contract requirements (e.g., furnishing bonds, etc.), the owner will execute and deliver an agreement to the contractor.

Number of Stops — Measure of effectiveness (MOE) of control systems which is an estimate of the number of vehicles stopped by traffic signals.

O&M — Operation and Maintenance.

Object Program — The machine language equivalent of a source program. The output of a language translator. A program that is ready to be loaded.

Objective — Statement of specific action that can be taken as a step toward achievement of a goal.

Occupancy — See ***Lane Occupancy***.

Occupancy Control — Traffic-responsive control strategy whereby metering rates are selected on the basis of real-time occupancy measurements taken upstream or downstream of the entrance ramp.

Offline — Descriptive of a system, peripheral equipment, or a process not under the control of the central processing unit. (See ***Online***.)

Offset — The time relationship expressed in seconds or percent of cycle length, determined by the difference between a defined interval portion of the coordinated phase green and a system reference point.

Offset Selection — Choosing one of several possible offsets manually or automatically either by time-of-day or in response to some directional characteristic of traffic flow.

Online — Descriptive of a system, peripheral equipment, or a process under control of the central processing unit. (See ***Offline***.)

Online Optimization — A method by which a process, i.e., traffic signal plan, is continually recomputed in real time to seek the best obtainable set of operating conditions.

Open-Loop System — Pertaining to a control system in which there is no self-correcting action or feedback as there is in a closed-loop system.

Open Specifications — Specifications written so as to allow several manufacturers to bid on materials and equipment.

Operand — A unit of data to be operated on, usually identified by the address portion of an instruction.

Operation Code (Opcode) — The portion of a computer instruction which designates the operation to be performed such as ***Add***, ***Subtract***, ***Input***, ***Output***, ***Logical Operations***, etc.

Operating Sytem — Computer software that performs the function of organizing and controlling the overall execution of the application software.

Operational Delay — Time lost as a result of interference between components of traffic. Included are delays caused by traffic movements that interfere with stream flow, such as parking and unparking vehicles, pedestrians, stalled vehicles, double parking, cross traffic, and merging/weaving maneuvers.

Optimum Density — Traffic-flow density (or concentration) which corresponds to maximum volume of traffic flow on a particular roadway.

Optimum Speed — Traffic-flow speed (vehicle movement) which corresponds to maximum volume of traffic flow on a particular roadway.

Optimization Programs — Programs that compute and evaluate the effects of various sets of signal timing on vehicle flow within a given network. These programs determine optimal timing plans and/or evaluate a given timing plan.

Origin-Destination Survey — Survey to determine the point of origin and the point of destination for a given vehicular trip.

Oscillator — An electronic or solid-state circuit used to generate alternating current signals.

Out-of-Step — A term used to describe a condition when one or more of the controller assemblies are not in coordination with the control system.

Output — Data transferred from a computer's internal storage unit to an external storage device or output device.

Overlap — A right-of-way indication that allows traffic movement when the right-of-way is being assigned to two or more traffic phases.

Overlay — The technique of repeatedly using the same blocks of internal storage during different stages of a program; e.g., when one routine is no longer needed in internal storage, another routine can use the same storage area.

Paralled Transmission — A method of simultaneously transmitting all of the bits that make up a digitally encoded character. Paralled transmission requires a separate linkage for carrying each bit.

Parameter — (1) A quantity in mathematics that may be assigned any arbitrary value and that remains constant during some calculation. (2) A definable characteristic of an item, device, or system.

Parity — The addition of noninformation bits to a character being transmitted in order to make the number of one bits in each character always be odd or even (optionally). At the receiver, the bits in each received character are checked to see that an odd number of one bits per character is received in order to detect errors in the received data. (See ***Error Detection***.)

Parity Check — A summation check in which the one bits in a character or word are added, and the sum checked against a single, previously computed parity bit; i.e., the check test whether the number of ones in a word is odd or even. (Same as ***Odd-Even Check***.)

Passage Period — The time allowed for a vehicle to travel at a selected speed from the detector to the nearest point of conflicting traffic.

Pattern — See ***Timing Plan***.

Pattern Generation — See ***Plan Generation***.

Pattern Matching — See ***Plan Matching***.

Pattern Selection — See ***Plan Selection***.

Payment Bond — Bond guaranteeing contractor's payment for materials, equipment, labor, and other items associated with the project.

Pedestrian-Actuated Controller Assembly — A controller assembly in which intervals, such as pedestrian WALK and clearance intervals, can be added to or included in the controller cycle by the actuation of a pedestrian detector.

Pedestrian Clearance Interval — The first clearance interval following the pedestrian WALK indication, normally flashing DON'T WALK.

Pedestrian Detector — A detector that is responsive to operation by or the presence of a pedestrian.

Pedestrian Phase — A traffic phase allocated to pedestrian traffic which may provide a right-of-way indication either concurrently with one or more vehicular phases, or to the exclusion of all vehicular phases.

Pedestrian Pushbutton — A momentary switch which, when activated by a pedestrian, causes a pulse which notes the demand by a pedestrian for the right-of-way.

Performance Bond — Bond guaranteeing contractor's completion of the project.

Peripheral Equipment — Various units or machines that are used mainly for input-output in combination or conjunction with the computer but are not part of the computer itself.

Phase — See ***Traffic Phase***.

Phase Modulation (PM) — A technique to transmit information using a sine wave signal. The sine wave, or "carrier," has its phase changed in accordance with the information to be transmitted.

Phase Sequence — A predetermined order in which the phases of a cycle occur.

Phase Shift Keying (PSK) — A modulation method employed to transmit data. The technique of differentially coherent phase modulation is generally used as it eliminates the difficulty of deriving a reference phase. In such a system, each signal element is stored one element at a time and the phase change between sucessive elements provides system coherence and the desired reference.

Pickup Procedures — The orderly processes or operations which are performed to bring a controller assembly under control of the system master.

Pixel — The smallest area on the screen of a graphics CRT display that can be discretely displayed by the system. ***Pixel*** is an abbreviation of ***Picture Element***.

PL/1 (Programming Language/One) — A compiler language that can be used with equal facility for both business and scientific applications. PL/I combines some of the features of COBOL and FORTRAN.

Plan Generation — The process of computing the traffic parameters forming a timing plan from accumulated traffic data and the area geometry.

Plan Matching — A technique used to select a timing plan based on comparing measured traffic data with stored data associated with a stored timing plan.

Plan Selection — Choosing one of several different timing plans, from a library of timing plans, either manually, or automatically as a function of time-of-day traffic-responsively.

Plans, Specifications, and Estimates (PS&E) — The documents that define the traffic control system design to potential installation contractors.

Point Detection — The detection of vehicles as they pass a specific point on the roadway. Detection by pressure and magnetometer detectors are typical examples. Frequently referred to as "small area detection."

Point-To-Point Connection — A communication link that connects only two data stations.

Polar Loop — A form of direct-wire linkage wherein the ON/OFF conditions are repre sented by DC voltages of opposite polarities. (See ***DC Multiplexing***.)

Polling System — A communications system that uses a systematic method, centrally controlled for permitting stations on a multipoint circuit to transmit without contending for the interconnect line.

Power Head — A small 3-ft by 6-ft (0.9 by 1.8 m) loop installed at the stop line end of a long loop in order to improve the detection of small vehicles.

Preemption — The transfer of the normal control of signals to a special signal control mode.

Prequalification — The process by which prospective bidders must prove their financial and technical capabilities to implement the proposed system before their bid will be accepted.

Presence Detection — The sensing of a vehicle passing over a detector. True presence is when the pulse duration is equal to the actual time the vehicle remains in the detector field of influence.

Presence Detector — Traffic detector which is able to detect the presence or absence of a vehicle within its field of detection.

Presence Holding Time — The time that a detector system will continue to indicate the presence of a vehicle over one of its loops without adjusting to consider the vehicle a new environment. Upon making this adjustment, the actuation is terminated.

Presence Loop Detector — An induction loop detector which is capable of detecting the presence of a standing or moving vehicle in any portion of the effective loop area (ITE).

Probe — The sensor form that is commonly used with a magnetometer-type detector (NEMA).

Pressure Detector — A vehicle detector that consists of a switch or switches, that closure of which by vehicle impact notes the passage of a vehicle or vehicle axle.

Pretimed Controller Assembly — A controller assembly for the operation of traffic signals with predetermined fixed cycle length, fixed interval duration, and fixed interval sequence.

Preventive Maintenance (PM) — Those work items that should be done, at scheduled intervals, to minimize the probability of equipment failure.

Process Control Computer — A computer whose primary purpose is to provide automation of continuous operations.

Processor Storage — A storage device which can hold data and instuctions for immediate retrieval by the CPU. Each byte or word of a storage is directly accessible. (Also called ***Memory*** or ***Core Storage*** or ***Internal Storage***.)

Program — A series of instructions or statements, in a form acceptable to a computer, prepared in order to achieve a certain result.

Programmable Read-Only Memory (PROM) — A device that stores data which cannot be altered by computer instructions. Data is stored ("burned") into this device by an external electronic process. Some PROM's can be erased and programmed through special physical processes. (See ***EPROM***.)

Progression — A term used to describe the progressive movement of traffic through several intersections within a control system without stopping.

Project Evaluation and Review Technique (PERT) — A technique of project management which relates the interdependency of project tasks based on time factors and insures a timely and coordinated project completion.

Pull Box — A container, usually 1 cu ft in size, that is placed underground with a removable cover flush within the ground line. Splices and conduit ends are located here.

Pulse Mode — The detector produces a short output pulse when detection occurs (NEMA). The pulse lasts only about 100 ms, even if the vehicle remains in the detection zone for a longer time.

Project Management — A technique that transforms a need to a reality in a controlled way.

Punched Card — A storage medium in which data are represented by means of holes punched in vertical columns of a card.

Punched Paper Tape — A storage medium in which the data are represented by means of holes punched in the tape.

Quadrupole — A loop configuration that adds a longitudinal sawslot along the center of the rectangle, so that the wire can be installed in a figure-8 pattern, thereby producing four electromagnetic poles instead of the normal two. The design improves the sensitivity to small vehicles and also minimizes splashover.

Queue Detector — Component of a traffic control system which senses the presence (or number) of vehicles waiting in a queue.

Queue Length — Number of vehicles that are stopped or moving in a line where the movement of each vehicle is constrained by that of the lead vehicle.

Radar Detector — A vehicle detector installed above or adjacent to the roadway capable of being activated by the passage of a vehicle through its field of emitted microwave energy.

Radio-Frequency Detector — A vehicle detector consisting of a loop of wire imbedded in the roadway that is tuned to receive a preselected radio frequency from a transmitter normally located on a vehicle.

Ramp Control — Regulation, warning, or guidance of traffic at points of access to or egress (exit) from a freeway.

Ramp Metering Signal — Traffic signal which directs entrance ramp vehicles to stop and permits them to proceed in accordance with metering rates determined by the type of entrance ramp control being used.

Random Access — The process of obtaining information from, or placing information into, storage where the time required for such access is independent of the location of the information.

Random Access Memory (RAM) — A storage device with both read and write capabilities which will allow random access to stored data.

Read-Only Memory (ROM) — A storage device programmed during manufacturing that cannot be changed. Synonymous with nonerasable storage and read-only storage.

Real-Time Batch Monitor (RBM) — System software which monitors the demands of the foreground processing so that as time becomes available, the system will be automatically freed to begin batch processing (background processing).

Real-Time Clock — A clock which indicates the passage of actual time of day rather than a clock set by the computer to measure an arbitrary interval of time.

Real-Time Control –- The processing of information or data in a sufficiently rapid manner so that the results of the processing are available in time to influence the process being monitored or controlled.

Real-Time Disk Operating System (RDOS) — Real-time system software using a disk medium for peripheral storage. (See ***Real-Time Control.***)

Real-Time Operating System (RTOS) — A computer program that controls the operation of a computer that must perform control functions in a timely manner. (See ***Real-Time Control and Operating System.***)

Real-Time System (RTS) — A computer system wherein a computation is performed during the actual time that the related physical process transpires, in order that results of the computation can be used in guiding the physical process.

Real-time, Traffic-Responsive Control System — Traffic control system which evaluates and selects control system which evaluates and selects control tactics continuously on the basis of current measures of traffic conditions.

Rear-Projection Readouts — Miniature projection device which can project images in the device to a small viewing screen that can be mounted in the surface of a display panel or map.

Recall — An operational mode for an actuated controller unit whereby a phase, either vehicle or pedestrian, is displayed each cycle whether or not demand exists. Usually a temporary or emergency situation.

Receiver — A part of the communication system which accepts and translates (decodes) signals into commands or data functions.

Recurrent Congestion — A type of congestion which is routinely expected at predictable locations during specific time periods.

Red Clearance Interval — A clearance interval which may follow the yellow interval during which both the terminating phase and the next right-of-way phase display red.

Reel — A spool of magnetic tape.

Register — A device used for the temporary storage of one or more words to facilitate arithmetic, logical, or transferral operations.

Relay — An electromagnetic switching device, having multiple electrical contacts, energized by electrical current through its coil. It is used to complete electrical circuits.

Remote Terminal — An input/output unit physically removed from the central facility but connected by means of a communication link.

Removable Disk Pack — A set of magnetic disks used in a processing device for reading and writing which can be interchanged with other disk packs. Common to moving head disk units.

Repeater — A device used to amplify and/or reshape signals.

Request for Proposal (RFP) — A written document inviting prospective bidders to submit a project proposal.

Reset — The action in an intersection controller which causes the control to begin its cycle at a new position in time in relation to a reference. Resetting a control assures a desired offset between intersections in a progression system at all times.

Resistance — The opposition that a device or material offers to the flow of direct current, equal to the voltage drop across the element divided by the current through the element.

Responsive Mode — A system operation wherein the selection of signal timing plans is based on current traffic data as input by vehicle and pedestrian detectors.

Rest-In-Red — A controller designed to display red to all movements, in the absence of any traffic demand.

Reversible Lane — A term used to describe a traffic lane upon which the direction of the flow of traffic may be varied during different periods of the day.

Roadside Radio — Type of driver information system by which messages are conveyed to motorists from local transmitters beside the roadway to radio receivers in their vehicles.

Rotating-Drum Sign — A sign which rotates selective message panels so as to display a single message panel or several message panels at any point in time.

Rotating-Tape Sign — A sign which has a number of messages on a tape or film, and which is mechanically capably of selecting and rotating a given message so that it can be viewed. Also referred to as rotating-film or windowshade sign.

Routine Maintenance — Those work items that must be done regularly to ensure that traffic signal equipment will continue to operate.

Sampling Detector — Any type of vehicle detector used to obtain representative traffic flow information (NEMA).

Sampling Period — The length of time between each sample of a sensor. (Equal to ***1/Sampling Rate***.)

Sampling Rate — The rate at which measurements of physical quantities are made. The number of times each second that the computer senses the status of a data sensor such as a loop detector.

Scanning System — A system which senses the status of multiple points, such as detectors, and/or transmits commands to multiple points such as controller units in a predetermined sequence and time schedule.

Search — A software procedure for the examination of a set of items for one or more having a given property.

Second-Generation Control (2-GC) — Online timing-plan generation wherein timing plans are updated periodically. This type of control program is based on a background cycle but provides for online real-time computation of timing plans. It utilizes a prediction model to predict near-term changes in traffic demand. These predictions are then used in an optimization program to develop the timing plan.

Secondary Controller Assembly — A controller assembly which operates traffic signals under the supervision of a master controller assembly. (Sometimes called a ***Slave***.)

Section — A group of signalized intersections which are interconnected and have some time relationship between them.

Self-Tracking Detector — A loop detector unit, not necessarily self-tuning, that includes electronics that compensate for environmental drift.

Self-Tuning Loop Detector Unit — One that is capable of adapting its operation to the resonant frequency of the loop and lead-in wire without any manual adjustment required. The term applies particularly to the startup of the detector's operation, upon turn-on. (Compare ***Self-Tracking Detector***.)

Semiactuated Traffic Controller Assembly — A type of traffic-actuated controller assembly in which means are provided for traffic actuation on one or more, but not all, approaches to an intersection.

Semiconductor — A material such as germanium or silicon whose conductivity is poor but is improved with additions of small amounts of impurities such as arsenic or antimony.

Sense Switch — A switch on the console of a computer that may be set to ON or OFF. Statements may be included in a program to vary the program execution based on these settings.

Sensitivity — As it relates to a loop system the change in total induction of a system caused by a minimum vehicle at one loop, expressed as a percentage of the total inductance. As it relates to a detector, is the minimum inductance change in percent required at the input terminals to cause the detector to actuate.

Sensor (System and Local) — Traffic detection devices (detectors) that permit the system master or a local controller to obtain information as to the traffic flow characteristics in the area of the sensor. (See ***Detector***.) NEMA limits the meaning of ***sensor*** to the sensing element of a detector.

Serial Transmission — A method of digital data transmission whereby the bits that represent an item of information are transmitted sequentially over a single channel.

Service Patrol — A patrol which provides assistance to those motorists in need of routine aid, such as fuel, oil, water, tire change, and minor mechanical repairs at the roadside.

Shield — A conductive material surrounding the pair of lead-in wires of a loop-detector installation, so that outside electrical interferences will not induce noise onto them.

Shock Wave — Boundary, moving upstream of an incident, between the region of traffic flow affected by the incident and that regional of traffic flow not affected by the incident.

Signal Control Strategy — The method of controlling an intersection so as to enhance the flow of traffic. Examples of control strategies are pretimed and actuated control. (Also see ***Actuated Controller Assembly***, ***Pretimed Controller Assembly***, and ***Full-Actuated Controller Assembly***.)

Signal Indication — The illumination of a signal lens (or an equivalent device) whereby the movement of vehicular or pedestrian traffic is controlled.

Signal Timing — The amount of time allocated to each interval/function in a signal cycle.

Signal-to-Noise Ratio (SNR) — A measure of the quality of a communications channel that relates the received signal strength to the strength of the unwanted signals (noise) that combine with the desired signal during transmission.

Silicon Slice — A thin piece of silicon on which integrated circuits are placed.

Simplex Channel — A one-way communications channel. One end of the channel is always the transmitter and the other end is always the receiver.

Simulation — A pseudo experimental analysis of a system by means of mathematical or physical models that operate in a time-sequential manner similar to the system itself.

Single Alternate — A signal timing plan where half-cycle offsets are used between each adjacent signalized intersection.

Single-Entry Metering — Method of entrance ramp control which permits only one vehicle to enter the freeway per ramp metering signal cycle.

Single-Message Sign — Sign which is capable of transmitting only one message to the driver.

Single-Mode Control — Ability of a control system to implement only one concept of control.

Single-Reset System — Reset system of direct interconnection of local controller units which provides only one offset.

Single-Ring Controller Unit — A single-ring controller unit contains two or more sequentially timed and individually selected conflicting phases so arranged as to occur in an established order.

Sinusoidal — A waveform having the shape of the mathematically defined sine wave. This wave shape is commonly used in defining frequency-related parameters in communications systems.

Skip Phasing — The ability of a controller unit to omit a phase in the absence of demand on that phase or as directed by a master control.

Slow-Vehicle Detector — Component of a merge control system which senses the presence of a slow-moving vehicle on the entrance ramp between the ramp metering signal and the merge detector.

Small Area Point Detector — A detector intended to detect vehicles at a spot location upstream of the stopline. They may detect more than one lane. The 6-ft (1.8m) loop detector is a prominent example.

Also, included are ultrasonic and radar units, whose detection areas may be as long as 20 to 30 ft (6 to 9 m), because the length of time the moving vehicle is in the detection zone is not used in the intersection control logic.

Small Scale Integration (SSI) — In integrated circuitry, a chip with fewer than 100 logic elements. (Also see ***Integrated Circuit*** and ***Logic Element***.)

Smoothed Data Value — A point or value representing the average trend of discrete data. This value is found by using a filtering equation which is an iterative approach. (Also see ***Filtering Equation***.)

Software — Various programs to facilitate the efficient operation of the system. Such software items include various assemblers, generators, subroutines, libraries, compilers, operating systems, and application programs.

Software Generations — A family of software routine related to each other in that each generation is a modification of the preceding routine. All generation have the same name and are distinguished from each other by their generation numbers (first, second, third) and their successive dates of creation.

Software Maintenance — Those tasks required to correct errors remaining in computer programs after they are placed in operation, as well as making other program modifications to meet the demands of changing system needs.

Sonic (Ultrasonic) Detector — A vehicle detector which emits sound energy from a transducer at a high frequency (one that is in the upper range of human hearing) and that senses the reflection of its energy off of a vehicle in its field.

Source File — A card deck, disk, drum, or magnetic tape containing a file of information used as input to a computer run.

Source Program — A program written in a nonmachine language such as FORTRAN. The program becomes the input to a language translator.

SPACE — One state in a 2-state system. (See ***MARK***.)

Space Mean Speed — The average of speeds of vehicles within a given space or section of roadway at a given instant; also, average speed of a specified group of vehicles based on their average travel time over a section of roadway.

Special Conditions — That portion of the contract documents which provides further explanation of general conditions or relates a general condition to a specific requirement associated with a project.

Special Event Plan — A timing plan stored in memory which is activated to compensate for unusual traffic flow caused by a special event (such as a football game).

Specifications — Written documents describing minimum requirements for items of work, materials, equipment, etc.

Splashover — An unwanted actuation caused by a vehicle in a lane adjacent to that in which the detector is located.

Split — A division of the cycle length allocated to each of the various phases. Normally expressed in percent.

Split Selection — The process by which a split is selected or calculated by the computer based on a measurement and comparison of directional demand as detected by system sensors or predetermined by time of day clock.

Standby Mode — An operational status of a local controller assembly or system which is not under central computer control but is capable of responding to central computer control.

Standby System — Local control components which operate the intersection signals upon failure of the communication link to the computer or when the intersection is in standby mode.

Standby Transition — The act of changing to or from a standby mode. (See ***Drop Procedures***, ***Pickup Procedures***.)

Starting Delay — A delay experienced in initiating the movement of queued traffic from a stop to a maximum flow rate through a signalized intersection.

Stops — The number of vehicles that stop. Used as a measure of effectiveness to assess the effectiveness of a timing pattern. A computer-controlled system goal is to minimize stops.

Store — The procedure by which one or more bytes of data are transferred from the CPU to processor storage.

Stored Plan — A timing plan in computer storage.

Strategical Concepts — Approaches that basically utilize timing plans that are predetermined and then called into use by the consideration of time of day or traffic flow as measured by traffic detectors. (Contrasted with ***Tactical***.)

Strategy — Procedure used to determine signal timing.

Street Equipment — That equipment or hardware which is located "on the street," such as an intersection controller assembly, signal heads, and detectors.

Stretch Detector (Extended Call Detector) — A detector with a carryover output. It holds or stretches the call of a vehicle for a period of seconds that has been set on an adjustable timer incorporated into the detector. It can be designed to begin the timing of that period when the vehicle enters the detection area, or when it leaves. The latter design is much more common.

Submaster Controller Assembly — A controller assembly which receives command from a master controller assembly and effects changes in timing plans to secondary controller assemblies.

Subnetwork — Subdivision of a section.

Subnetwork Control — A control technique in which a signal system consisting of numerous signalized intersections is subdivided into two or more subnetwork for control purposes.

Subroutine — (1) The sequence of machine instructions that complete a defined function or program. (2) A program that defines desired operations and which may be included in another program to produce the desired operations.

Subroutine Library — A collection of subroutines.

Supervisor — Software that controls and schedules the other software routines.

Surveillance — The monitoring of traffic performance and control system operation.

Synchronization — In communications, the process by which a transmitter and a receiver coordinate their operation so as to properly identify the bits an characters that make up a digitally transmitted message.

Synchronous Controller Unit — A controller unit in which the timing mechanism is controlled by and dependent on a suitable frequency standard such as the frequency of the alternating-current source.

Synchronous Data Transmission — A type of data transmission in which each character consists of 5-8 information bits depending on the code structure. There are no start and stops bits. Timing is derived through synchronizing characters at the beginning of each message or block of data. (See ***Asynchrounous Data Transmission***.)

Sync Pulse — A pulse generated from a central point that provides a common time base to all coordinated traffic controller units and which is used to provide a smooth flow of traffic through coordinated intersections.

Synthesis — The combination of parts, elements, etc., to form a working and coherent whole.

System — An array of components designed to achieve an objective according to a given or developed plan.

System Performance Evaluation — The determination of the relative merits of system improvements.

System Shutdown — (1) Emergency system shutdown involves the failsafe turning off of some or all system components due to power failure or equipment failures. (2) Planned system shutdown consists of the turning off of some or all system components by manual or automatic means, usually for maintenance or offline tasks.

System Speed (or Average Overall Travel Speed) — The ratio of total travel to total travel time.

System Status — A display or printout of the operational condition of each monitored unit in the system.

Systems Approach — An arrangement or combination of interacting or independent parts which form a unified whole serving a common purpose. In developing a traffic control system, these parts include problem identification, feasibility analysis, system evaluation and selection, system design, installation, operation, and maintenance. The significance of the ***Systems Approach*** is that, during performance of each part, all other and their interactive impacts are carefully considered.

Systems Management — The act of directing, coordinating, and/or controlling the design and implementation phases of a system.

Table — An array of data each item of which may be unambiguously identified by mean of one or more subscripts.

Table Lookup — (1) A processs of obtaining information previously stored rather than creating information based on calculations. (2) In control systems, the process of selecting prestored timing plans rather than generating timing programs based on real-time calculations.

Tape Frame — A data representation area on a paper tape or magnetic tape which holds one character of information. A frame is oriented perpendicular to the length of the tape.

Tape Punch — A device which stores data in the form of punched holes on a tape, usually paper. Hole locations are arranged in columns across the width

416

of the tape. There are usually 5-8 positions per column, with data represented by a binary coded system. All holes in a column are sensed simultaneously in a manner similar to that for punch cards. (Synonymous with ***Tape Perforation***.)

Tape Reader — (1) A peripheral device capable of sensing information recorded on a magnetic tape in the form of a series of magnetized spots. (2) A device capable of sensing information punched on a paper tape in the form of a series of holes.

Tape Track — The same bit position on successive tape frames. Analogous to a punched card row. A track parallels the edge of the tape.

Tariff — The published rate for a particular commercial service of a common carrier.

Telegraph Grade Circuit — A circuit in which the maximum signaling rate is 75 baud, generally considered sufficient for teletypewriter transmission. A circuit suitable for direct current transmission.

Telemetering, Telemetry — The automatic transmission of data over long distances.

Telephone Call-In System — One type of driver information system which provides traffic information upon request via telephone to be used for pretrip planning.

Teletypewriter (TTY) — An input-output device with a keyboard which produces printed words and possibly punched tape. Frequently, it is connected directly to the CPU and is used to provide the operator with direct communications with the computer.

Third-Generation Control (3-GC) — Online timing-plan generation wherein timing plans will be updated on a cycle-by-cycle basis or some caparable time frequency. It is envisioned that it will be a significant advance in real-time dynamic control. The requirement for a constant or background cycle will probably be eliminated. More numerous and more sophisticated detectors will probably be required, along with considerably more complex software.

Threshold — A present level or value of a parameter which indicates that a change of activity will occur if the current value is above or below this level.

Through-Band — The area between a pair of parallel speed lines which delineate a progresssive movement on a time-space chart.

Throughput — Traffic moving from beginning to end of a roadway in the direction of major flow. Throughput connotes traffic being put into a facility at one end and taken out at the opposite end, and may be expressed in conventional volume terms (vehicles per time period) or in vehicle-miles per time period.

Time-Base Coordination — Traffic signal coordination based on an internal electronic clock, rather than an interconnect.

Time Division Multiplexing (TDM) — A technique for transmitting several different messages over one pair of wires by dividing a fixed interval of time into several time slots in which a discrete message is sent in each time slot.

Time Headway — The time separation between vehicles approaching an intersection, measured from front of vehicle to front of vehicle.

Time-Of-Day Operation (TOD) — Signal timing plans selected according to time of day.

Time Mean Speed — The average of speeds of all vehicles or a specified class of vehicles at a specific point on a roadway during a specified period of time; also called average spot speed.

Time Share — The use of a device for two or more purposes during the same overall time interval, accomplished by interspersing component actions in time.

Timing Key — The device placed in a dial unit to effect a change in signal indication or check for coordination.

Timing Plan — A set of cycle length, splits, and offsets within a section of signals. The particular timing for each intersection may vary with time of day within the plan.

Tone — An audio frequency signal.

Total Travel — A term used to designate the total person- or vehicle-miles of travel on a roadway during a time period of interest.

Total Travel Time — The sum of individual vehicle travel times along a specific roadway section or route. Usually expressed in terms of vehicle-hours per unit of time.

Trace Routine — A routine that provides a historical record of specified events in the execution of a program. Used primarily in debugging programs.

Traffic-Adjusted System — A system in which an analog computer controls cycle length at special local controller assemblies.

Traffic Control — Regulation, warning, and guidance of traffic for the purpose of improving the safety and efficiency of traffic flow.

Traffic Detector — A device located in or near the roadway, which is acted upon directly by a vehicle to create a usable pulse to an intersection control device.

Traffic Generators/Attractors — Major activity centers, such as parking garges, shopping centers, etc., which generate or attract traffic.

Traffic Phase — Those right-of-way, change, and clearance intervals in a cycle assigned to any independent movement(s) of traffic.

Traffic-Responsive System — A system in which a master controller (analog or digital) either selects or computes signal timing based on the real-time demands of traffic as sensed by vehicle detectors.

Transceiver — A communications device used both to trasmit and receive information. A transmitter and receiver on common chassis.

Transducer — A device that is actuated by power from one system, and that supplies power in any other form to a second system.

Transfer Rate — The speed at which data may be read from or written to the device.

Transition — The process or processes whereby the system master and the local intersection controller units change from one program to another.

Transmission — The electrical transfer of a signal, message, or data from one point to another.

TRANSYT — An offline traffic signal timing optimization program developed in England. ***TRANSYT-7F*** — An Americanized form of the original program, TRANSYT-7F was developed under Federal Highway Administration sponsorship.

Triple-Reset System — Reset system of direct interconnection of local controller units which provides three offsets.

Truth Table — A mathematical concept which can be used to represent the relationship between events. Shows the result of a given logical expression for some combination of input values.

Turbulent Flow — See ***Unstable flow***.

Two-Abreast Metering — A form of platoon metering which releases two vehicles side by side per ramp metering signal cycle.

Ultra Violet Erasable Programmable Read Only Memory (UVEPROM) — An EPROM that is erased and reprogrammed using ultra violet light.

Unconditioned Line — A voice-grade private line data channel (such as the 3002-type channel) without compensation to minimize attenuation in the audiofrequency band. (See ***Voice-Grade Line***.)

Unstable Flow — The operating condition where a small increase in demand (flow) can be expected to be accompanied by a large decrease in speed leading to high densities and internal friction. This type of high-density operation cannot persist, and it leads inevitably to congested flow.

Upstream — The roadway portion which is positioned toward the source of approaching traffic from the point of reference.

User-Assistance Software — All of the programs which extend the capabilities of the hardware and which made the hardware more easily usable. This usually includes functions of controlling and scheduling execution of programs, controlling input-ouput, data management, language translation and related services. (Also called the ***Operating System***.)

UTCS-1 — See ***NETSIM***.

Utility/Cost Analysis — An evaluation procedure used for analyzing the ability of a traffic control system to perform its function in comparison to its cost.

Utility Measure — A proxy value used as a measure of the benefit, or utility, of a traffic control system.

Variable Initial Interval — A controller unit design feature which adjusts the duration of initial interval for the number of vehicles in the queue.

Variable-Speed Control — Concept of mainline control which limits the speed of traffic on a freeway in accordance with prevailing traffic conditions.

Vehicle Detector System — A system for indicating the presence or passage of vehicle (NEMA). (See ***Detector System***.)

Vehicle Display — Equipment, for displaying information to drivers, that is mounted within the vehicle.

Vehicle Extension — The amount of time, in seconds, that a green interval is extended for each vehicle actuation on a traffic-actuated controller assembly.

Vehicle or Pedestrian Recall — A feature on a traffic-actuated controller unit which will allow the selection of any phase to which the unit will automatically return after it has served the other phases.

Verify — To determine whether a transcription of data or other operation has been accomplished accurately. To check the results of keypunching.

Very Large Scale Integration (VLSI) — In integrated circuitry, a silicon chip with 100,000 or more logic elements.

Video Display Terminal (VDT) — Used by some manufacturers to designate the combination of the CRT display with a keyboard.

VOC — Volume and Occupancy Constant.

Voice-Grade Lines — A channel suitable for transmission of speech, digital, or analog data, or facsimile, generally with a frequency range of about 300-3,000 Hz.

Volatile Memory — A storage medium in which information is destroyed when power is removed.

Volume — The number of vehicles passing a given point per unit of time.

Volume-Density Controller Unit — A type of actuated controller unit which has added initial and gap-reduction timing features.

Watchdog Timer — A timing device designed to detect faults resulting from a lack of response from a remote-controlled machine.

Weighted Sensor Data — Information received from a detector which has been adjusted according to a preset value.

Wide-Band Channel — A channel having a bandwidth greater than that of a voice-grade channel. Wide-band channels having bandwidths from 50,000 Hz to over one million Hz (a video channel) are available but not in common use in traffic systems.

Word — A group of consecutive bits which occupy one processor memory location and most frequently (but not always) are used in a standard computer instruction or operand.

Word Length — (1) The number of bits in a computer word. In a given computer, the number may be constant or variable. (2) The number of usable storage bits in a computer word.

Yellow Change Interval — The first interval following the green right-of-way interval in which the signal indication for that phase is yellow.

Yield (YLD) — A command which permits transfer of the right-of-way.

ALPHABETICAL INDEX

AAP-85 – 3.25, 3.26

ACTUATED CONTROLLERS IN 1-GC – 3.34

ADJUSTMENTS, IN METERING RATES, FOR TRAFFIC-RESPONSIVE SYSTEM – 4.20

ADVISORY INFORMATION –
  route guider – 4.3
  speed – 4.3
  travel time – 4.3

AERIAL SURVEILLANCE, FOR INCIDENT DETECTION – 4.44

AGENCY RESPONSIBILITY, FOR TRAFFIC CONTROL SYSTEMS –
  area of responsibility – 2.4
  existing hardware – 2.4
  HOV use – 2.4
  special features – 2.4
  system size – 2.4
  traffic control system similarities – 2.4

ALGORITHMS – 3.65
  incident detection, pattern-recognition, time-series – 4.42

AMPLITUDE MODULATION (AM) – 8.7

ANALYSIS, BETWEEN PERCENT STOPPING AND APPROACH DELAY – 3.66
  delay-offset – 3.58
  full-actuated phasings – 3.58

ANSI FORTRAN – 4.54
  use for computer simulation models – 4.54

APPLICATIONS, ACTUATED – 3.16

AREAWIDE SYSTEM CONTROL – 3.43
  centralized control system – 3.43

ARTERIAL (OPEN NETWORK) TRAFFIC SIGNAL SYSTEM – 7.3

ARTERIAL SIGNAL COORDINATION DESIGN, SOFTWARE MODELS – 3.25, 3.26

ARTERIAL STREET CONTROL, SYSTEMS OF – 3.22

ARTERIALS, URBAN –
  flow quality, analyzed by average speed – 3.66

BALI (BASIC ARTERIAL LOCAL INTERSECTION) – 7.10, 7.11, 7.12

BAM (BASIC ARTERIAL MASTER) – 7.10, 7.11, 7.12

BANDWIDTH – 3.22, 3.29

BASIC INTERVAL TIMING FUNCTIONS – 6.12

BINARY TRANSMISSION SYSTEMS – 8.6

BOTTLENECKS, FREEWAY – 4.6

BROAD EMERGENCY ASSISTANCE RADIO SYSTEM (BEAR), DETROIT, AND GRAND RAPIDS – 4.45

BUS PRIORITY SYSTEMS, RESEARCH ON – 3.61

BUS PRIORITY SYSTEM – 3.61
  through-bus – 3.61
  stop bus – 3.61

CABLE, TWISTED-PAIR – 8.15
  private-line voiceband – 8.15

CALIFORNIA, DETECTOR ELECTRONIC DESIGN, MODEL 170 – 5.5

CALTRANS (CALIFORNIA DEPARTMENT OF TRANSPORTATION), "CALIFORNIA ALGORITHM" – 4.42
  diamond interchange software – 3.53

CAMBRIDGE SYSTEMATICS –
  travel demand forecasting – 3.49

CAMERAS, FOR FREEWAY INCIDENT DETECTION – 4.50

CAPACITY, REDUCTIONS IN, MAINLINE – 4.32

CATV – 8.20

CENTER FOR HIGHWAY RESEARCH, UNIVERSITY OF TEXAS – 3.21

CENTRAL BUSINESS DISTRICT (CBD) – 2.6, 3.28

CENTRAL PROCESSING UNIT (CPU) – 7.31, 7.32

CENTRALIZED INTERVAL COMMAND SYSTEMS – 2.3

CHANGEABLE-MESSAGE SIGNS (CMS) – 9.4-9.11

CHANNEL SPECIFICATIONS, LOCAL – 8.16

CHICAGO AREA EMERGENCY TRAFFIC PATROL, FOR MOTORIST AID – 4.47

CHICAGO, INCIDENT DETECTION – 5.30

CHICAGO, KENNEDY EXPRESSWAY, REVERSIBLE LANE CONTROL – 4.38

CITIZEN-BAND (CB) RADIO, AS MOTORIST AID – 4.45, 4.46

CLOSED CIRCUIT TELEVISION (CCTV) - 4.39, 4.44
  system components - 4.50

CLOSED NETWORK CONTROL - 3.28
  section configuration - 3.40

CLOSED NETWORK SIGNAL TIMING - 3.30

CLOSURE IN RAMP CONTROL - ES.3

COAXIAL CABLE - 2.7

COMMUNICATION LINKS (ONE-WAY/TWO-WAY) - 8.13
  interconnection - 8.4, 8.5
  quality - 2.6
  reliability - 8.26
  transmission rates - 8.25ff

COMMUNICATIONS, ALTERNATIVE LINKS -
  air-path communications, laser and microwave - 8.24
  coaxial cable - 8.17
    cable TV (CATV) - 8.18
    owned vs. shared - 8.18
  fiber-optic communication - 8.22
  wire pairs, owned vs. leased - 8.15

COMMUNICATIONS INTERFACE UNIT - 8.14

COMMUNICATIONS PROTOCOL IN 1-GC - 3.34

COMMUNICATIONS TECHNOLOGY - 8.3
  basic concepts in traffic control systems - 8.4
  channel bandwidth - 8.9
  closed-loop - 8.7
  FSK/PSK - 8.9
  historical development - 8.3
  impact on traffic control systems - 8.3
  information sources - 8.31
    air-path communications - 8.33
    coaxial cable (CATV) - 8.32
    data communication - 8.32
    fiber-optic communication - 8.33
  interconnection - 8.5
  interface equipment - 8.14
    interface unit - 8.14
    modems - 8.14
  laser - 8.24
  modulation/demodulation - 8.6
  multiplexing - 8.1
  one-way vs. two-way links - 8.13
  techniques in communications links and signaling - 8.4

COMMUNICATIONS, TRAFFIC CONTROL SYSTEMS - 2.9

COMMUNICATIONS SYSTEM, PLANNING AND EVALUATION - 8.25

COMPLEXITY, OF SYSTEM MASTERS - 12.15

COMPUTER, CENTRAL (SEE ALSO CENTRAL PROCESSING UNIT) - 8.7

COMPUTER FAILURE, BACKUP FOR - 5.18

COMPUTER SIMULATION - 3.15

COMPUTER SOFTWARE, FOR FREEWAY OFFLINE TESTING AND ONLINE CONTROL - 4.51

COMPUTER SOFTWARE MODELS, CORQ-CORCON - 4.51, 4.52

COMPUTER TECHNIQUES, IN TIMING PLAN DEVELOPMENT - 3.30

CONCURRENT FLOW LANES. FREEWAY, HOV USE - 4.58, 4.59

CONFIGURATION, VEHICLE DETECTOR - 5.14

CONGESTION, ANALYSIS, TOTAL MINUTE-MILES - 3.66

CONGESTION, AND INTEGRATED RAMP CONTROL - 4.25

CONGESTION, FREEWAY - 4.3, 4.4
  causes - 4.5, 4.6, 4.7
  characteristic effects - 4.1
  control techniques - 5.26
  geometric design - 4.4
  nonrecurring - 4.3, 4.4
  random - 4.4
  recurring - 4.3, 5.26

CONTRACT DOCUMENTS -
  system design/implementation - 11.8
    agreement - 11.9
    bid proposal - 11.8
    bonds - 11.8
    conditions - 11.9
    contractor qualifications - 11.9
    instructions to bidders - 11.8
    invitation to bid - 11.8
    precedence - 11.9

CONTRAFLOW LANES, FREEWAY, HOV USE - 4.58, 4.59, 4.60

CONTROL -
  first-generation (1-GC) - 3.32, 3.33, 3.34, 3.35
  fixed-time - 3.56
  fixed-sequence - freeway mainline - 4.36
  freeway surveillance - 5.26
  second-generation (2-GC) - 3.32
  third-generation (3-GC) - 3.33

CONTROL -
  closed network - 3.25, 3.28
  corridor, in freeway operation, purpose and objectives - 4.39
  demand-capacity - 4.18
  diamond interchange, basic phasing schemes - 3.51
  entrance ramp - 4.7
  exit ramp - 4.33
  freeway - ES.3, 1.3
    corridor - ES.3
    mainline - ES.3
    ramp - ES.3
  freeway use of computer models - 4.50, 4.51, 4.52
  freeway and urban street, cooperative development - 2.10
  gap-acceptance merge - 4.21
  high-occupancy vehicle (HOV) priority - 4.56
  integrated ramp, defined - 4.25
  isolated signal and signal system - 3.53

  isolated vs. system, basic factors in – 3.27
  levels and benefits of – 4.31
  levels and incremental benefits – 3.45
  loop-occupancy – 5.13
    large area – 5.15
  mainline, applications – 4.33
  modes for diamond interchange signals – 3.53
  occupancy – 4.18
  strategy for bus priority – 3.60
  street intersection – 6.5
  traffic-actuated, principal modes of operation – 3.14
  traffic signal systems, surveillance subsystem – 5.18
  TRSP plan generation, different types of – 5.23 5.25
  urban streets – ES.2, 1.3, 1.4
    individual or isolated intersection or open network – ES.1, 1.3, 1.4
  variable-speed – 4.33 4.34
  volume-density, characteristics – 6.5

CONTROL AND SURVEILLANCE, FREEWAY SYSTEM, EVIDENT RESPONSE AND REMOVAL – 4.46, 4.47

CONTROL CENTERS, FEATURES – 7.37

CONTROL CENTER MONITOR ARRANGEMENT PERIPHERAL DEVICES, TRANSMISSION SYSTEMS – 4.50

CONTROL CONCEPTS – ES2 1.3, 1.4
  freeway control – 4.3
    corridor control – 4.3
    mainline control – 4.3
    ramp control – 4.3
  traffic signals, basic categories of – 3.11
    areawide system – 3.3
    arterial intersection (open network) – 3.3
    closed network – 3.3
    isolated intersection, – 3.3
    operational experience in – 4.3
    signalized intersection, categories of – 3.3
  urban street control, list of – ES.2

CONTROL SYSTEM –
  concepts, areawide, geographic elements – 3.42
  freeway applications of – 4.3-4.63
  gap-acceptance merge components – 4.23
  gap-acceptance merge evaluation – 4.24
  master – 2.3
  multijurisdictional – 3.45
  multilevel, decentralized, disadvantages of – 3.45
  networks – 5.22
    Basic system – 2.6
    mid-range systems – 2.6
    sophisticated systems – 2.6
    Wide Area Detection System (WADS) – 5.32
  traffic-responsive, dependence on detectors – 5.3ff
  traffic signal, goal of – 3.45

CONTROL TECHNIQUES –
  experience with online, by the United States, Great Britain, and Canada – 3.36, 3.37
  offline – 3.25
  online – 3.26
    traffic-responsive – 3.36
  traffic – 3.60

CONTROL VARIABLES, SENSED BY DETECTORS (ALSO SEE CHAPTER 5) – 3.3
  types commonly used – 3.3

CONTROLLABILITY INDEX – 4.31

CONTROLLER –
  assemblies, software – 3.33
  full-actuated – 3.26
  local – 4.11, 4.18, 7.4
  Model 170 unit – 3.54
  NEMA, full-actuated unit – 3.54
  operation in gap-acceptance merge system – 4.23
  pretimed – 2.7, 3.53
  Texas Diamond – 3.55

CONTROLLER SYSTEMS –
  traffic-responsive arterial master – 5.21

CONTROLLER UNIT –
  arterial master – 5.21
  central processing unit (CPU) – 7.31, 7.32
  local – 4.18, 7.4

CONTROLLER/DETECTOR RELATIONSHIP – 5.12

CONTROLLERS, FULL-ACTUATED DETECTION MODES – 6.11
  locking detection memory – 5.12, 6.11
  nonlocking detection memory – 5.12, 6.11

CONTROLLERS, FULL-ACTUATED – 6.10
  timing and phasing characteristics – 6.11
  single-and dual-ring – 6.12
  basic interval timing – 6.12
  special features – 6.13
  down-loading capabilities – 6.20
  hardware characteristics, environmental and operational requirements – 6.17
  operation – 6.10, 6.11
  system capabilities – 6.20

CONTROLLERS, LOCAL (SEE CHAPTER 6) –
  hardware development – 6.7
  interconnection, physical – 6.29
  Model 170 software – 6.23
  pretimed controllers – 6.8
    coordination requirements – 6.10
    electromechanical – 6.8, 6.9
    solid-state digital – 6.8, 6.10
  range of applications – 6.5
  special controls – 6.5
  types – 6.8
  types of operation – 6.3
  comparison of NEMA and Model 170 – 6.26
  coordination, by function – 6.28
  Model 170 – 6.21
  NEMA – 6.26

CONTROLLERS –
  selection of system, factors in – 6.30
    human element – 6.32
    implementability and flexibility – 6.31
    maintenance/reliability – 6.31

COOPERATION, BASIS FOR FUTURE TRAFFIC CONTROL DEVELOPMENT – 2.10

COORDINATION –
  local controllers – 6.28
  forms of interconnection – 6.29

    air-path communication, physical – 6.29
    time-base – 6.29
  time-base, for system masters – 7.14

CORQ-CORCON, COMPUTER SIMULATION MODELS – 4.50, 4.51, 4.52

CORRIDOR CONTROL, STRATEGIES OF RESTRICTION AND DIVERSION – 4.41

CORRIDOR CONTROL AND SURVEILLANCE IN FREEWAY OPERATION – 4.39-4.50

COST-EFFECTIVENESS OF TRAFFIC-RESPONSIVE METERING – 2.4, 2.7, 12.7 (ALSO SEE CHAPTER 4)

CRITICAL INTERSECTION CONTROL – 3.40

CRITICAL MOVEMENT, ANALYSIS, INTERSECTION TIMINGS – 3.18

CRT (CATHODE RAY TUBE) – 3.45, 7.18, 7.32
  console – 7.38

CTS (CLEAR TO SEND), TRANSMISSION – 8.15

CYCLE LENGTH – 3.14, 3.16, 3.19, 3.22

CYCLE SPLITS – 3.22

DAFT (SCOT FAMILY) – 4.51, 4.52, 4.55

DARTS SYSTEM (DYNAMIC ARTERY RESPONSIVE TRAFFIC SIGNAL SYSTEM) – 3.26
  application examples – 7.10

DATA-BASE MANAGEMENT, SOFTWARE FOR – 3.33

DATA TRANSMISSION, REAL-TIME – 8.27

DELAY – 5.20

DELIVERABLE SERVICES, SYSTEM – 11.11-11.14

DEMAND/CAPACITY RELATIONSHIP TO FREEWAY CONGESTION – 4.7

DETECTOR –
  actuations and signal timing, relationship – 3.64
  location – 6.4
  long-loop – 3.13
  self-powered vehicle (SPVD), developed by FHWA – 5.31

DETECTION –
  comparison of single- and multiple-point – 5.14
  high-speed approaches – 5.13
  incident, freeway examination for nonrecurring problems, cities using – 5.30
  locking memory – 5.12
  low-speed approaches (less than 35 mph) – 5.12
  nonlocking memory – 5.12
  small-vehicle – 5.18
  traffic regulation, by mainline control – 5.28
  variables, presence and passage, for system operation and evaluation – 5.20

DETECTION SYSTEMS VEHICLE – 3.61

DETECTORS (ALSO SEE CHAPTER 5) – 2.7, 3.10, 3.11
  demand – 4.12
  effective length, for vehicles – 5.20
  guidelines for spotting – 5.26
  inductive loop (ILD) – 5.3ff
  large-area – 5.15
  large-area, left-turn lane use – 5.15
  lateral placement of – 5.24
  location and spacing – 4.44
  location for system operation evaluation – 5.24
  longitudinal placement – 5.25
  loop, for control system use – 2.7
  merge, queue, continued actuation, in metering adjustment – 4.19
  passive bus – 5.9
  small-area – 5.14
  types of – 5.3
  types of, in freeway surveillance and control – 5.26
  types used for freeway surveillance and controls – 5.26

DETECTOR, VEHICLE, LOCATION AND CONFIGURATION – 5.14

DETECTOR/CONTROLLER –
  design – 5.13
  relationship – 5.12

DETROIT CCTV SURVEILLANCE FOR INCIDENT DETECTION – 4.49

DETROIT INCIDENT DETECTION – 5.30

DETROIT MOTORIST AID BY BEAR SYSTEM – 4.45

DETROIT SCANDI – 5.20

DEVELOPMENT, TECHNICAL/RESEARCH, TO BE LIMITED IN FUTURE – 2.10

DEVELOPMENT OF TIMING PLAN, MANUAL TECHNIQUES FOR – 3.29

DIAGRAM, TIME-SPACE – 3.65

DIAGRAMMATIC SIGNS – 9.4ff

DISK STORAGE, MAGNETIC – 7.39

DISPLAY OF INFORMATION, BY COMPUTER COLOR GRAPHICS – 2.10

DISPLAY OF TRAFFIC FLOW DATA AND SYSTEM STATUS – 2.7

DISTRIBUTED INTELLIGENCE – 2.4

DIVERT, ONLINE COMPUTER SIMULATION MODEL – 4.56

DRIVER INFORMATION, REAL-TIME DISPLAY – 2.7

DRIVER INFORMATION SYSTEMS (ALSO SEE CHAPTER 9) – 9.3
  cellular mobile phone system – 9.22
  citizen band (CB) radio – 9.20
    BEAR system – 9.20
    CB/Aids – 9.21
  commercial radios – 9.22
  design guide – 9.23
  Highway Advisory Radio (HAR) – 9.13

  motorist aid systems, call box/emergency telephone - 9.18
  signs, types - 9.3-9.13
    diagrammatic - 9.4
    static - 9.3
    transportable - 9.11
  signs, types - 9.3-9.13
    changeable message (CMS) - 9.6
      display - 9.6
      electromechanical - 9.9
      light source - 9.7
      mechanical - 9.6
      static - 9.3
  transportation management center - 9.23

DVPRO, DRIVER VEHICLE SOFTWARE PROCESSOR - 3.21

EMERGENCY CALL BOXES AND TELEPHONES, AS MOTORIST AIDS - 4.45

ENTRANCE RAMP CLOSURE -
  limitations - 4.9, 4.10
  simplest/most positive form of control - 4.9

ENTRANCE RAMP CONTROL (SEE CHAPTER 4) -
  for increased freeway capacity - 4.8

ENTRANCE RAMP METERING - 4.10
  applications - 4.10, 4.11
  purpose - 4.10
  results - 4.10

ENVIRONMENTAL DETECTORS - 5.3, 5.9

ENVIRONMENTAL FACTORS, AS CONTROL VARIABLES - 3.3

ENVIRONMENTAL SENSORS (ALSO SEE CHAPTER 5) - 3.3

EQUATIONS (SEE CHAPTERS 3,4,5) -

EUREKA (CALIFORNIA) DISTRIBUTED MULTILEVEL SYSTEM (EDIPS) - 5.21, 7.15

EVALUATION, AS FINAL STEP IN PROCESS CONTROL SYSTEM LOOP - 2.4

EVALUATION OF TRAFFIC CONTROL SYSTEMS - 12.18-12.20

EXECUTIVE SUMMARY - ES.1

EXIT RAMP CONTROL - 4.33

EXPERIENCE, NEEDS IN TRAFFIC CONTROL SYSTEM STAFFING - 12.13

FACTORS, IN CONTROLLER SELECTION - 6.30
  effects/costs - 6.31
  operating requirements/constraints - 6.30

FACTS - 3.53
  mini computer control - 5.21, 7.7

FACTS SYSTEM (FLEXIBLE ADVANCED COMPUTER TRAFFIC SIGNAL SYSTEM) - 3.27, 7.7

FALSE ALARM, RATES OF, IN INCIDENT DETECTION SYSTEMS - 5.30

FEATURES OF CONTROL CENTERS FOR SYSTEM MASTERS - 7.37
  new control - 12.10

FEDERAL-AID REGULATIONS - 10.3, A.1

FEDERAL COMMUNICATIONS COMMISSION (FCC), LICENSING BY - 5.8

FEDERAL HIGHWAY ADMINISTRATION (FHWA) - ES.1, 1.3, 3.38, 3.47, 3.66, 6.8, 7.25
  Traffic Detection Handbook - 5.5

FIBER-OPTIC CABLE, USE IN TRAFFIC CONTROL SYSTEMS - 2.9

FILTERING AND SMOOTHING MODEL, AN ALGORITHM USED IN PROCESSING TRAFFIC DATA - 3.9

FIRMWARE (SEE SOFTWARE) -

FIXED-RATE METERING - 4.23

FLEXIBILITY, IN NEW TECHNOLOGY - 12.3

FLOW-UNBALANCED AND/OR REVERSIBLE-LANE OFF-CENTER - 3.59, 3.60

FLOW RATE - 3.3, 3.6
  capacity - 3.6
  speed-density relationship - 4.17
  vehicle and saturation - 3.16

FLOW RATE AND DENSITY -
  as MOE for freeway congestion - 4.4

FORCAST, SOFTWARE - 3.35

FORTRAN (IV) - 3.31, 3.38, 4.51, 7.18, 7.28

FREQ MODEL FAMILY - 4.51, 4.53

FREEWAY CORRIDOR CONTROL AND SURVEILLANCE - 4.39-4.50

FREEWAY TRAFFIC CONTROL -
  diversion strategies for - 4.8
  entrance ramp metering, widely used - 4.7

FREEWAYS -
  applications of control systems to - 4.3-4.63
  bottleneck - 4.1
  control systems for, defined - 1.5
  mainline metering to improve operations - 4.36
  purpose, defined - 4.3

FREEWAY SURVEILLANCE AND CONTROL, IN VARIOUS CITIES, TYPES OF TRAFFIC CONTROL GROUPS - 5.27

FREEWAY TRAFFIC CONTROL (ALSO SEE CONTROL) ENTRANCE RAMP METERING, MOST WIDELY USED FORM, LEVELS OF - ED.3

FUEL CONSUMPTION, ESTIMATING - 3.45, 3.46

FULL-ACTUATED CONTROLLERS - 6.10

GAP ACCEPTANCE, BASIC CONCEPTS OF - 4.21

GAP-ACCEPTANCE MERGE-CONTROL, SYSTEM - 4.24
  - evaluation - 4.24
  - operation - 4.23

GAP-OUT - 3.13, 5.14

GENERAL SYSTEM OPERATION - 12.5
  - data collection/analysis - 12.5
  - documentation - 12.5
    - monitoring and intervention - 12.5

GEOPRO, SOFTWARE PROCESSOR - 3.21

GEOMETRIC DESIGN FACTORS, CAUSING CAPACITY REDUCTION - 4.4

GERMANY (WEST), TRAFFIC SYSTEMS IN - 4.35

GREEN EXTENSION, LIMIT BY PRESET MAXIMUM - 6.11

GREEN INTERVAL - 3.65

GUIDELINES FOR SPOTTING DETECTORS - 5.26

GUIDELINES BY ITE COMMITTEE, 6A-16, FOR IMPLEMENTING HOV LANES - 4.61

HANDBOOK, TRAFFIC CONTROL SYSTEMS (UPDATED) - ES.1, 1.6 (SEE ALSO TABLE OF CONTENTS)
  - how to use - 1.6
  - purposes of - ES.1, 1.3
  - review of - 4.41
  - scope/objectives - ES.1, 1.3

HARDWARE, ADVANCES IN - ES.1

HARDWARE, STATE-OF-THE-ART, FOR CONTROL SYSTEMS - ES.3
  - communications - ES.3
  - detectors - ES.3
  - driver information systems - ES-3
  - local controllers - ES.3
  - sytem masters - ES.3

HEADWAY AS CONTROL VARIABLE - 3.3, 3.8

HIGH-INTENSITY LIGHT EMISSION - 5.3, 5.8

HIGH-OCCUPANCY VEHICLE (HOV) PRIORITY - 3.60
  - control - 3.60
  - separated facilities - 4.56

HIGHWAY ADVISORY RADIO (HAR) - 9.13-9.18

HIGHWAY USER COSTS, ESTIMATING - 3.47

HOLD COMMAND - 7.5

HONEYWELL COMPUTER (FLORIDA) - 7.28

HOUSTON FREEWAY OPERATIONS - 4.35

HOV (HIGH-OCCUPANCY VEHICLE), LANE USE GUIDLINES, BY ITE COMMITTEE, 6A-16 - 4.61

HOV LANE CONTROL - 2.4
  - exclusive ramps for - 4.61

HOV, PRIORITY TREATMENT OF - 2.5
  - METERED RAMP BYPASS - 4.61

HOV USAGE -
  - reserved freeway lanes, concurrent flow and contraflow - 4.58

HYSTERESIS, IN FREEWAY CONGESTION - 4.6

ILLINOIS DEPARTMENT OF TRANSPORTATION (IDOT), SERVICE TO MOTORIST AID - 4.48

IMPLEMENTATION SYSTEM, DESIGN AND - 11.3-11.6, 11.17

INCIDENT DETECTION, BY AERIAL SURVEILLANCE - 4.44
  - freeway, by police and service patrols - 4.46
  - television surveillance for - 4.49

INCIDENT MANAGEMENT -
  - freeway control - 4.41
    - detection - 4.1, 4.41
    - response - 4.1, 4.4

INDUCTIVE LOOP DETECTORS (ILD) - 5.3ff, 5.26

INFORMATION SOURCES, COMMUNICATION TECHNOLOGY - 8.31

INFORMATION SYSTEMS, DRIVER - 9.3

INFRARED BEAM DETECTORS - 5.3

INITIAL TIMING - 6.4

INPUT DEVICES, FROM PERIPHERALS, IN 1-GC - 3.34

INSTALLATIONS, CUSTOM-DESIGNED - 2.6
  - Committee, 6A-16, guidelines for implementing HOV lanes - 4.61

INSTITUTE OF TRANSPORTATION ENGINEERS (ITE), STANDARDS FOR VEHICLE DETECTORS - 5.6

INTEGRATED PRETIMED METERING DEFINED, OPERATIONS INFORMATION - 4.25

INTEGRATED RAMP CONTROL -
  - applied to various systems - 4.25
  - ramp metering - ES.3
  - responsive metering - 4.29

INTERACTION, NEEDS FOR STAFF AND MAINTENANCE PERSONNEL - 12.11

INTERCHANGE, DIAMOND - 3.51, 3.53, 3.56
  - Texas Diamond Controller - 3.56
  - urban interchange - 3.56, 7.8

INTERCHANGES, SIGNALIZED DIAMOND - 3.58

H25

INTERSECTION CAPACITY – 3.14

INTERSECTION CONTROL – 3.60
  bus priority – 3.60, 3.61
  isolated actuated – 5.14

INTERSECTION CONTROLLER UNIT, PRIMARY FUNCTION – 6.3

INTERSECTION TIMING – 3.18
  computer software fo – 3.21
  critical movement analysis – 3.18
  publications on – 3.19
  requirements – 3.14
  traffic-actual control – 3.19
  Webster – 3.15

INTERSECTIONS, URBAN STREET – 3.65

INTRAS – 4.51, 4.53, 4.54

ISOLATED ACTUATED INTERSECTION CONTROL – 5.14

ISOLATED INTERSECTION CONTROL –
  basic considerations – 3.14
  operational considerations – 3.14

INTERCONNECTION, COMMUNICATION – 8.5

ITALY, TUNNEL CONTROL BY LANE CLOSURE – 4.35

JAPAN, FREEWAY OPERATION MAINLINE CONTROL IN – 4.33, 4.36

KETTERING (OHIO) TESTS BY, ON SPVD DETECTORS – 5.31, 5.32

LAMP DISPLAYS (CMS) IN OPERATIONS, VARIOUS LOCATIONS – 9.9

LANE BLOCKAGE, ADVANCE WARNING OF, ON FREEWAYS – 4.35

LANE CHANGES, IN MERGING, SAFETY PROBLEM – 4.11

LANE CLOSURE, FREEWAY – 4.33, 4.35
  to reduce congestion and improve entrance ramp merging – 4.35
  traffic diversion – 4.35

LANE OCCUPANCY – 4.18

LANE-USE CONTROL SIGNALS – 9.25

LASER, TRANSCEIVER – 8.24

LEFT-TURN LANES, LARGE-AREA DETECTION – 5.15

LINK SELECTION – 5.23

LINKS – 8.4
  direct-coupled – 8.4
  polar-loop – 8.4

LOCAL CONTROLLERS – 2.7

LOCAL INTERSECTION PREEMPTION, GROUPING OF, BY SECTIONS OR SUBNETWORKS – 3.34

LOCKING DETECTION MEMORY – 5.12, 6.4, 6.11

LOGIC, EXTERNAL OR INTERNAL – 6.18

LOOP CHARACTERISTICS, IN DETECTOR SENSITIVITY – 5.4

LOOP ELECTRONICS, IN DETECTOR DESIGN – 5.5

LOS ANGELES –
  ATSAC System – 5.24
  Los Angeles Area Freeway Surveillance and Control Project (LAAFSCP) – 4.44, 4.48, 4.49
  carpool bypass lane – 4.63
  incident detection – 5.30

MACK FAMILY – 4.51, 4.54

MAGNETIC DETECTORS, PROBE CHARACTERISTICS – 5.3, 5.6

MAGNETOMETERS – 5.26
  detectors – 5.3
  probe characteristics – 5.6

MALFUNCTION DETECTION – 7.32

MAINTENANCE/CONSTRUCTION, EFFECT ON FREEWAY CAPACITY – 4.6

MAINTENANCE –
  dealing with malfunctions – 2.5
  inadequate, problems from – 12.16
  ongoing cost and importance to system success – 2.7
  for TCS; types – 12.14
    functional – 12.14
    hardware – 12.14
    software – 12.14
  skills needed – 12.17

MANUAL PLAN SELECTION – 3.35

MANUAL TECHNIQUES –
  offline computer techniques – 3.24
  timing plan development – 3.29

MASTER SIGNAL CONTROL SYSTEM, COST OF – 3.50

MAXBAND, ANALYSIS OF – 3.25

MAXIMUM INTERVAL, AS TIMING PARAMETER – 3.11

MEASURES OF EFFECTIVENESS (MOE'S) – 2.4, 2.7, 12.7

MOE, ASSEMBLY INTO USABLE FORM FOR GENERAL OPERATIONAL ANALYSIS – 12.7
  delay, most widely used in traffic control – 3.65
  number and percentage of stops – 3.6
  stopped-vehicle delay – 3.65
  total travel – 3.64
  total travel time – 3.62

MOE'S, COMMON – 7.27, 12.21
  accident rate reduction – 12.21

- corridor throughput – 12.21
- delay – 12.21
- number/percentage of stops – 12.21
- total minute-miles of congestion – 12.21
- total travel time – 12.21
- total vehicle-miles of travel – 12.21

MERGE CONTROL –
- gap-acceptance – 4.21
- in ramp metering – ES.3

METERING –
- freeway-to-freeway connector – 4.36
- platoon and single-entry – 4.13
- rate selection, single-entry, traffic-responsive – 4.19
- traffic-responsive, influenced by mainline and ramp traffic – 4.15

MICROPROCESSORS, USE OF, IN TRAFFIC CONTROL SYSTEMS – ES.3
- basic timing parameter – 3.11, 3.12

MINIMUM GREEN INTERVAL, IN SEMIACTUATED AND ACTUATED CONTROL – 3.11, 6.4

MINIMUM GREEN TIME – 3.13

MINNEAPOLIS, MAINLINE METERING, FREEWAY-TO-FREEWAY CONNECTOR METERING – 4.36
- ramp metering layout with bypass – 4.62

MOBILITY, URBAN – ES.1, 1.3

MODE –
- isolated interchange – 3.56
- lane-occupancy – 3.14
- operational (TOD) – 3.60
- queue length – 3.14
- semiactuated and full-actuated – 3.14
- volume-density – 3.14

MODEL 170 – 6.8
- controller unit – 2.7, 3.54
- controllers – 2.7, 6.8

MODIFIED NEMA-TYPE AND MODEL 170 UNITS, CAPABILITIES – 6.20

MODULATION/DEMODULATION – 8.6

MOTORIST-AID SYSTEMS – 4.45, 4.46, 9.18

MOVEMENT –
- directional – 3.60
- turning – 3.58

MULTIJURISDICTIONAL SYSTEM – 2.10

MULTIPLEXING –
- frequency-division (FDM) – 2.9
- time-division (TDM) – 2.9
- multipair cables – 2.9

MUTCD – 3.41

NASA 1 SYSTEM – 7.8

NCHRP, PROJECT 3-18, GUIDELINE DEVELOPMENT, OVERSATURATED STREET NETWORKS – 3.41

NEMA (NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION) – 2.7, 3.26, 3.53
- controllers – 6.8, 6.21, 7.21
- definitions of signal phasing, published by MUTCD – 3.10
- full-actuated controller – 3.54
- identification of differences in detector unit design – 5.4, 5.5ff

NETGRAF, INTERACTIVE GRAPHIC CAPABILITY FOR NETSIM – 3.39

NETSIM MODEL (NETWORK SIMULATION MODEL) – 3.38

NETSIM/BPS MODEL – 3.39

NETWORK CONTROL SYSTEMS – 5.22

NETWORK (CLOSED GRID PATTERN), TRAFFIC SIGNAL SYSTEM – 7.3

NETWORK SATURATION – 3.41

NEW YORK, DETECTOR ELECTRONIC DESIGN REQUIREMENTS, MODEL 170 – 5.5

NEW YORK, POLYTECHNIC INSTITUTE, NCHRP REPORT 194 – 3.41

NONLOCKING DETECTION MEMORY – 5.12

NONRECURRENT CONGESTION, ON FREEWAYS –

NYDOT (NEW YORK DEPARTMENT OF TRANSPORTATION) – 6.23

OCCUPANCY – 5.20
- density – 3.3, 3.6

OFFLINE COMPUTER SOFTWARE MODELS, EXPERIENCE WITH – 3.31

OFFLINE COMPUTER TECHNIQUES – 3.24, 3.25

OFFSET VALUE – 3.22

ONLINE COMPUTER MODELS, DIVERT AND STAR – 4.56

OPERATIONAL MODES, IN TRAFFIC-ACTUATED CONTROL – 3.14, 12.4ff

OPERATIONAL PERIODS IN TRAFFIC CONTROL, APPROACHES – 12.4

OPTIMUM SETTINGS, WEBSTER, FOR CRITICAL LANE – 3.16

OPTIONS, IN TRANSPORTATION SYSTEM MANAGEMENT (TSM), RANGE OF – 2.5

ORIGINATION/DESTINATION STUDIES, USE OF COMPUTER MODELS FOR – 4.52

OVERLAND PARK, AND LEASED CATV FACILITIES – 8.21

OVERRIDE OF SIGNAL TIMING – 7.35

PASSER II – 5.20
  updating – 12.8

PASSER II-80 – 7.7

PASSER-II(84), ANALYSIS OF – 3.25

PASSER-III MODEL (PROGRESSIVE ANALYSIS AND SIGNAL SYSTEM EVALUATION ROUTINE, MODEL III), TIME-BASED OPTIMIZATION – 3.58

PASSIVE BUS DETECTOR – 5.9

PEAK-HOUR PERIOD – 2.4

PEDESTRIAN –
  control – 3.41
  crossing signals for (such as walk/dont walk) – 3.13, 3.13
  detectors, pushbutton and vibration plate, for right-of-way – 5.3, 5.9
  movement single – 3.10, 3.19
  signals, walk/dont walk – 3.41

PHASE LENGTH – 3.14

PHASE RETURNS IN 1-GC – 3.34

PHASING – 3.13
  analysis of – 3.18
  changes in periods – 3.19
  patterns, sequences – 3.56

PHASING (SKIP), VARIABLE-SEQUENCE – 3.10

PHASES, IN CRITICAL INTERSECTION CONTROL – 3.40

PHOTOCELL DETECTORS – 5.3

PLATOON METERING – 4.12

PREEMPTION, FIRE OR EMERGENCY VEHICLE – 2.4

PREEMPTION SYSTEM, FLASHING-SIGNAL – 3.61
  greenband – 3.61
  high-occupancy and emergency vehicles – 3.6, 3.61

PREFERENTIAL OFFSETS, FOR BUSES – 3.60

PRESET INTERVAL(S) – 3.13

PRESSURE DETECTORS – 5.3, 5.7, 5.8

PRETIMED CONTROLLERS – 2.7
  coordinated – 3.26

PRETIMED METERING IN RAMP CONTROL – ES.3
  system components for – 4.11
  system evaluation, benefits – 4.14
  strategies for congestion – 4.16
  system operation – 4.12

PRETIMED SYSTEMS, EARLY – 1.4, 1.5

PRIORITY TREATMENT (HOV OPERATION) – 4.3

PROBLEMS, RESULT OF INADEQUATE MAINTENANCE – 12.16

PROM (PROGRAMMABLE READ-ONLY MEMORY) – 6.10

QUEUE –
  clearance intervals – 3.58
  detectors for – 4.18
  freeway corridors – 4.52
  length, as control variable – 3.3, 3.9, 5.20

RADAR DETECTORS – 5.3, 5.7, 5.8

RADIO-FREQUENCY DETECTORS – 5.3

RAM (RANDOM ACCESS MEMORY) – 6.10

RAMP CONTROL –
  integrated pretimed metering, example calculations – 4.26, 4.27, 4.29, 4.30
  integrated vs. independent – 4.31

RANDOM FACTORS, IN FREEWAY CONGESTION – 4.6

RECURRENT CONGESTION, ON FREEWAYS – 4.1

RED CLEARANCE INTERVAL – 3.20

RED INTERVAL – 3.14

REFERENCES (SEE END OF EACH CHAPTER) –

REFERENCES –
  driver information systems – 9.25
  selection of a system – 10.10
  system design and implementation – 11.22

REPORT, ON –
  general signalization information – 3.59
  optimal progression solution – 3.59
  phase interval – 3.59

RESTRICTED ENTRY – 4.3
  closure – 4.3
  metering – 4.3

RIGHT-OF-WAY, SPECIAL ASSIGNMENT OF – 3.60

RIGHT-TURN-ON-RED (RTOR) – 2.5

RIGHT-OF-WAY – 3.14

SAMPLING, PERIODIC, BY COMPUTER – 3.8

SAN BERNARDINO (CALIFORNIA), SEPARATED HOV TRAFFIC – 4.56, 4.57

SAN DIEGO, MAINLINE METERING IN FREEWAY CONTROL, CONNECTOR METERING – 4.36

SAN FRANCISCO –
  mainline metering in freeway control – 4.36
  Oakland Bay Bridge, incident detection – 5.30

SANTA MONICA (CALIFORNIA), ADD-A-LANE – 4.60

SATURATED FLOW CONDITIONS IN CLOSED NETWORK CONTROL – 3.40

SCAT – 3.38

SCOT MODEL, DAFT, NETSIM – 4.51, 4.54

SCOOT (SPLIT, CYCLE, AND OFFSET OPTIMIZATION TECHNIQUE), DESCRIPTION OF – 3.36, 3.38

SEATTLE (WASHINGTON), INCIDENT DETECTION – 5.30
  Interstate 5, reversible lane control – 4.38

SECTION CONTROL – 3.39

SELF-POWERED VEHICLE DETECTOR (SPVD), FHWA DEVELOPED – 5.31

SEMIACTUATED CONTROL CHARACTERISTICS – 6.4

SHIRLEY HIGHWAY (SEE WASHINGTON, D.C.) – 4.57

SIGNAL –
  control, traffic-actuated, basic timing parameters – 3.11
  network, grid pattern – 3.29
  phasing – 3.27
  system improvement, comprehensive, cost savings – 3.50
  system interconnection and optimization – 3.50
  timing – 7.32
  timing, for closed network – 3.28
  changes, needs – 12.9

SIGNALIZATION, PROBLEMS IN – 3.51

SIGNALIZED INTERSECTION CONTROL, DEFINITION OF BASIC TERMS – 3.9, 7.3

SIGNS, FOR DRIVER INFORMATION (SEE DRIVER INFORMATION SYSTEMS) –

SIGOP, PROGRAM SYSTEM UPDATING – 12.8
  software – 3.35

SIGOP III, ANALYSIS OF, CLOSED NETWORK – 3.25, 5.20
  model – 3.31

SINGLE-ENTRY METERING – 4.13

SOAP-84 MODEL – 3.21

SOFTWARE, ARTERIAL MASTER SYSTEMS – 7.6
  basic arterial system (BASYS) – 7.10
  DARTS systems – 7.8
  FACTS system – 7.6
  arterial signal coordination design – 3.25

SOFTWARE, AVAILABLE TECHNOLOGY – 2.10
  real-time control, for signal switching application – 2.10
  optimization and timing plan development – 2.10
  simulation models (CORQ-CORCON, FREQ, INTRAS, MACK, NETSIM, SCOT et al.) – 2.10

SOFTWARE, AVAILABILITY OF – 7.39
  private sector – 7.39
  public domain – 7.40
      Caltrans diamond interchange – 3.53

SOFTWARE COMPUTER SIMULATION MODELS, FOR OFFLINE TESTING AND ONLINE CONTROL – 4.51

SOFTWARE –
  intersection timing – 3.21
  Model 170 – 6.23
  Model for Basic Arterial Program (BASYS) – 6.26
  Model 170 – 6.23
  Diamond Interchange Program (DIP) – 6.24
    isolated traffic-actuated program (ITAP) – 6.23
    Local Intersection Program (LIP) – 6.23
  models for timing plan development – 3.30
  optional control and other features – 7.34
    backup techniques – 7.36
    controller down-loading and up-loading – 7.36
    equipment malfunction detection and failure reporting – 7.35
    memory overlay preemption – 7.37, 7.35
    unattended system operation – 7.37
  UTCS – 7.25
    first-generation extended and enhanced – 7.28
    1½-generation control – 7.30
  UTCS Enhanced, demonstration of – 2.10

SOFTWARE UPDATES – 12.10
  modification, additions, new features, for traffic systems – 12.10
  private sector – 7.39
  public domain – 7.39, 7.40

SOLID-STATE CONTROLLERS, ADVANTAGES – 6.10

SONIC DETECTORS – 5.3, 5.8

SPECIAL EVENTS, EFFECT ON TRAFFIC CONTROL – 2.4

SPEED – 3.3, 3.6, 5.20
  average link – 3.58
  space-mean – 5.20

SPLIT CALCULATION – 3.19

STAFFING FOR TRAFFIC CONTROL SYSTEMS, FACTORS AND NEEDS – 12.11

STAR, ONLINE COMPUTER SIMULATION MODEL – 4.56

STATIC SIGNS, FOR DRIVER INFORMATION – 9.3

STOPS – 5.20

STRATEGIES –
  freeway, ramp control and surveillance detector designs for – 5.27
  traffic-responsive metering – 4.18
  transportation systems management (TSM) – 2.5
    supply type – 2.5
    demand type – 2.5

STREET INTERSECTION CONTROL –
  applications, range – 6.5
  arterial system – 6.5
  isolated intersection – 6.5
  network system – 6.5

- SURVEILLANCE CAPABILITY, GEOGRAPHIC LOCATION OF, SINGLE DECENTRALIZED MULTILEVEL SYSTEM HARDWARE, HIERARCHICAL CONFIGURATION – ES.2

- SURVEILLANCE, CONTROL, AND DRIVER INFORMATION (SCANDI) SYSTEM, DETROIT – 5.20

- SURVEILLANCE –
  - concepts for detection – 4.42
  - control concepts, freeways – 4.3
  - control measure – ES.3
  - electronic – 4.42
  - freeway control system objective – 4.39
  - freeway incident detection, major methods for – 4.42
  - freeway system operation – 4.39
  - key element in corridor control – 4.40

- SURVEILLANCE SUBSYSTEM, OPTIONAL CONTROL – 7.34

- SYSTEM, BASIC COMPUTERIZED SIGNAL – 7.25

- SYSTEM COMPONENTS, IN TRAFFIC-RESPONSIVE METERING – 4.18

- SYSTEM CONTROL, AREAWIDE ADVANTAGES – 3.42
  - basic factors in – 3.27
  - decentralized, multilevel – 3.44

- SYSTEM DESIGN –
  - contract documents – 11.8
  - plans and specifications – 11.3, 11.6
    - closed vs. open – 11.7
    - functional vs. material – 11.8
    - specification sources – 11.7
    - standard types – 11.8
    - technical specifications – 11.9

- SYSTEM DESIGN AND IMPEMENTATION – 11.3, 11.6
  - procurement approaches – 11.4
    - approach comparison – 11.6
    - engineer (consultant)/contractor – 11.4
    - systems manager – 11.5
    - two-step procurement – 11.5

- SYSTEM IMPLEMENTATION – 11.3
  - deliverable services – 11.11
    - documentation – 11.11
    - maintenance – 11.13
    - startup – 11.13
    - system acceptance test – 11.14
    - systems management – 11.11
    - training – 11.12
    - warranties/guaranties – 11.13
  - pitfalls –
    - contractor inexperience – 11.18
    - construction management – 11.19
    - data base development – 11.21
    - insufficient staff (operations and management) – 11.21
    - maintenance staff alteration/alienation – 11.22
    - planned use of untested facility and utility coordination – 11.22

- SYSTEMS DEVELOPMENT –
  - construction phase – 11.3
  - design plans and specifications – 11.3
  - package-type – 7.32, 7.34
  - systems management – 11.3
  - training, debugging, documentation, evaluation, turnover – 11.4

- SYSTEM MASTER, AS MAJOR COMPONENT OVERSEEING TRAFFIC SIGNAL SYSTEM – 7.3

- SYSTEM MASTERS – 2.7
  - analog computer system – 7.4
  - electromechanical – 7.3
  - distributed closed-loop systems – 7.15
    - Econolite KMC-10,000 System – 7.21
    - EDIPS, Model 170 System, – 7.15
    - JHK Distributed Traffic control and surveillance system – 7.18
    - Safetran CM1655 System – 7.23
    - Transyt-7 3800 Closed-Loop System – 7.20
  - network control – 7.31
    - custom-designed – 7.32
      - package-type – 7.32

- SYSTEM OPERATION, GAP-ACCEPTANCE MERGE, OVERRIDE FEATURES – 4.23
  - integrated traffic-responsive metering – 4.29, 4.31
  - traffic-responsive metering – 4.19

- SYSTEM SELECTION, CRITERIA FOR – 2.6
  - traffic control, goals of – 3.62
  - traffic-responsive, evaluation – 4.21
  - traffic signal, ILC applications for – 5.19
  - network control – 5.22

- SYSTEM PROCUREMENT, DESIGN AND IMPLEMENTATION IN – ES.3

- SYSTEM SELECTION – 10.3
  - definition of system requirements – 10.5
  - evaluation of alternative systems – 10.5
    - utility and benefits, cost analysis – 10.6
  - identification of alternative systems – 10.5
  - selection of best system – 10.8
  - system requirements – 10.5
  - Federal-aid requirements – 10.3
    - operations plan – 10.5
    - policy and eligibility – 10.3
    - traffic engineering analysis, types of – 10.3, 10.4, 10.5

- SYSTEMS, ARTERIAL AND SMALL NETWORK – 7.4
  - actuated coordination units – 7.5
  - arterial masters – 7.6
  - arterial and small network – 7.6
  - arterial and small network, manufacturers' versions – 7.12
    - Eagle MC880 System – 7.12
    - Econolite EMC-10,000 System – 7.13
    - LFE/Automatic KB200 – 7.12
    - Master System – PRC Voorhees Micro Control System – 7.13
    - Safetran CM1630 System – 7.13
    - Safetran Model 170 Arterial System – 7.12
    - TRAC System – 7.13
    - Traconex HMM-200 System – 7.14
  - arterial street – 5.20ff

- SYSTEMS COMMUNICATION, PLANNING AND EVALUATION – 8.25
  - communication link quality – 8.26
  - communication link reliability – 8.26
  - trade-off on alternatives – 8.26
  - transmission rate, selection – 8.25

  utility/cost analysis – 8.31

SYSTEMS, DRIVER INFORMATION – 4.33, 4.34, 9.3
  gap-acceptance merge control – 4.23
  traffic surveillance and control – ES.1, ES.2, ES.3, 1.3, 1.4

TAMPA (FLORIDA) LOW-COST FREEWAY INCIDENT-MANAGEMENT DEMONSTRATION PROJECT – 4.49, 5.30

TCS (TRAFFIC CONTROL SYSTEM), REAL-WORLD ENVIRONMENT – 12.4

TDM – 8.18

TDM/FSK – 7.12

TEAMWORK IN SYSTEM MANAGEMENT, CONCEPT – 12.3

TECHNIQUES, TRAFFIC-RESPONSIVE – 3.60

TECHNOLOGY, AVAILABLE CONTROL SYSTEMS – 2.3
  advances in – 2.3
  decision-making about – 2.3
  detectors, use in data gathering – 2.3
  functions of – 2.3
  signal indications, control equipment for – 2.3

TECHNOLOGY, AVAILABLE HARDWARE – 2.7

TELEPHONE PAIRS, LEASED, USE OF – 2.9

TELEVISION SURVEILLANCE, CLOSED CIRCUIT (CCTV) – 3.62, 3.63

TEXAS DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION – 3.27, 3.55

TEXAS MODEL – 3.21

TEXAS TRANSPORTATION INSTITUTE – 3.58

THROUGH-BAND – 3.22

TIME-BASE COORDINATORS – 2.7
  system supervision – 7.3

TIME-SPACE DIAGRAM, DEFINITIONS OF TERMS FOR – 3.22

TIMING, OPTIMAL SIGNAL – 3.60

TIMING PERIODS – 3.21

TIMING PLANS FOR ARTERIAL SIGNAL SYSTEMS, COMPUTATION OF – 3.25, 7.3
  arterial streets, traffic flow variations, types of – 3.22
  development manual and offline computer techniques – 3.24
  elements – 3.22
  generation, online – 3.27

TIMING PLANS – 3.18
  online – 3.36

TOD (TIME OF DAY) REFERENCE – 7.35

TORONTO, USE OF COMPUTER MODELS IN FREEWAY STUDY – 4.52

TRAFFIC CONTROL –
  closed-loop process – 2.4
  full-actuated – 3.10
  volume and occupancy variables – 5.20

TRAFFIC CONTROL CONCEPTS, URBAN STREET – 3.3

TRAFFIC CONTROL SYSTEMS, FUNCTIONS OF – ES.1, 1.2, 2.3
  design (see system design) – 11.6
  implementation (see system implementation) – 11.3
  implementation – 2.5
    incidental benefits – 2.5
    reliability – 2.5
    traffic operations – 2.5
  objectives – 2.5
    adaptability – 2.5

TRAFFIC CONTROL SYSTEM OPERATION – 12.19
  communication applications – 8.8
  evaluation – 12.19
  maintenance – 12.13
  range of available options – ES.2
  use of fiber-optic cable in – 2.9
  validity – 12.19, 12.20

TRAFFIC CONTROLS, SPECIAL APPLICATIONS TO SIGNALIZED INTERSECTIONS – 3.51

TRAFFIC DEMAND PATTERN – 4.32

TRAFFIC DETECTOR SURVEILLANCE MEASURES AS CONTROL PARAMETERS – 5.3

TRAFFIC DIVERSION, ON FREEWAYS, BY LANE CLOSURE – 4.35

TRAFFIC FLOW, DIRECTION AND VOLUME OF, IN BASIC CONDITIONS – 3.23, 3.24
  control concepts for arterial streets – 3.22
  individual intersections – 3.23
  influenced by human activity – 3.20
  relationships – 4.16

TRAFFIC OPERATIONS FACTORS IN FREEWAY CONGESTION – 4.4

TRAFFIC-RESPONSIVE CONTROL SYSTEM, DEPENDENCE ON DETECTORS – 5.3

TRAFFIC-RESPONSIVE METERING –
  integrated – 4.29
    ramp control – ES.3
    system cost-effectiveness – 4.21
    system evaluation – 4.21

TRAFFIC SIGNAL TIMING PARAMETERS – 3.9
  cycle length – 3.9
  interval – 3.9
  offset – 3.9
  phase – 3.9
  split – 3.9

TRAFFIC SIGNAL TIMING PLAN OPTIMIZATION, COST-EFFECTIVENESS – 3.49

- TRAFFIC SIGNAL SYSTEM IMPROVEMENT –
  - costs of comparisons – 3.49
  - impacts – 3.47
  - project level and areawide – 3.47
  - timing variables – 5.20
- TRAFFIC SIGNAL SYSTEMS, CITIZEN CONFIDENCE IN – ES.1
  - research on, by FHWA office of planning – ES.2
  - rate and impact of – ES.1
  - surveillance subsystem – 5.18
- TRAFFIC SURVEILLANCE AND CONTROL SYSTEMS – 1.6
- TRANSPORTABLE SIGNS – 9.11
- TRANSPORTATION RESEARCH BOARD, PUBLICATION BY – 3.18
- TRANSPORTATION MANAGEMENT CENTER – 9.23
- TRANSPORTATION SYSTEM MANAGEMENT (TSM), NEED FOR, IN OPERATION OF TRAFFIC CONTROL SYSTEMS – ES.3, 1.4
- TRANSYT (TRAFFIC NETWORK STUDY TOOL) PROGRAM SYSTEM UPDATING – 12.8
- TRANSYT-7F –
  - assignment of transit priorities – 3.60
  - assured analysis of closed network – 3.25
  - program for optimization and timing plan – 2.10, 5.20
- TRRL (TRANSPORT AND ROAD RESEARCH LABORATORY, ENGLAND) – 3.36
- TRAVEL TIMES – 5.20
- TRSP-PLAN GENERATION – 5.22, 5.23
- TUNNEL CONTROL, BY LANE CLOSURE – 4.35
- UNATTENDED OPERATION, FOR ACTUATED CONTROLLERS – 3.34
- UNATTENDED SYSTEM OPERATION – 7.35
- UNITED KINGDOM, FREEWAY OPERATION IN – 4.33
- UNITED STATES, FREEWAY OPERATION, MAINLINE CONTROL – 4.33
- UNIVERSITY OF WASHINGTON, DESIGNER OF NETGRAF – 3.39
- URBAN OPERATING ENVIRONMENTS RELATED TO TRANSPORTATION SYSTEMS MANAGEMENT (TSM) – 2.5
- URBAN STREETS, NUMBER OF STOPS AND QUALITY OF FLOW – 3.64
- URBAN STREET, TRAFFIC CONTROL SYSTEMS FOR, FIRST SIGNAL ESTABLISHED IN – 1.4
- URBAN TRAFFIC CONTROL SYSTEM (UTCS) – 5.9, 7.13, 7.25
  - UTCS First-Generation Enhanced and Extended – 3.32, 3.33, 3.34, 3.35
  - (UTCS) 1½-Generation Control software – 3.35
- U.S. DEPARTMENT OF TRANSPORTATION, FEDERAL HIGHWAY ADMINISTRATION – ES.3
- U.S. ENVIRONMENTAL PROTECTION AGENCY (EPA), AND VEHICLE EMISSION DATA – 3.47
- VEHICLE DECAL, FOR AUTHORIZED VEHICLE LANE (AVL) WHICH INCLUDES HOV – 4.58
- VEHICLE DETECTORS, COMPARISON OF – 5.9
- VEHICLE DETECTION SYSTEMS – 3.61
- VEHICLE EMISSION, ESTIMATING – 3.46, 3.47
- VEHICLE LENGTH, IN CRITICAL MOVEMENT ANALYSIS – 3.18
- VEHICLE INTERVAL, AS BASIC TIMING PARAMETER – 3.11
- VEHICLE PASSAGE TIME INTERVAL – 3.13
- VEHICLE PRESENCE, DETECTION – 3.3, 3.6, 7.35
- VEHICLE VOLUME, AS DETECTION VARIABLE – 5.20
- VEHICULAR MOVEMENT, SINGLE – 3.9
- VERIFICATION, IN CONTROL DECISIONS, AS SURVEILLANCE FUNCTION – 2.4
- VOLUME – 5.20
- VOLUME/CAPACITY, AS CONGESTION CAUSE – 4.5
- VOLUME AND OCCUPANCY SURVEILLANCE – 7.13
- WALL-MAP DISPLAY, PART OF SOPHISTICATED SYSTEM – 2.7
- WASHINGTON, D.C., SHIRLEY HIGHWAY (I-395), SEPARATED HOV FACILITIES – 4.57
- WEATHER, AS CONTROL VARIABLE – 3.3
- WIRE, SINGLE OR PAIR OR MULTIPAIR CABLES, COST OF – 2.7, 7.3
- YELLOW CHANGE INTERVAL – 3.13, 3.20
- YIELD COMMAND – 7.5

METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha

MASS (weight)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons(2000 lb)	0.9	tonnes	t

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

INCHES
1
2
3
4
5
6
7
8
9
CM
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares(10,000m^2)	2.5	acres	

MASS (weight)

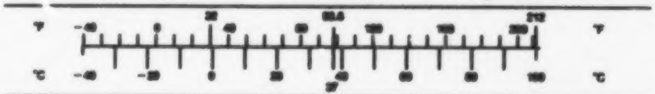
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000kg)	1.1	short tons	

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



433

To: U.S. Department of Transportation
Federal Highway Administration

The undersigned is an owner/user of ***TRAFFIC CONTROL SYSTEMS HANDBOOK*** (1985 Update).

I am interested in keeping updated on future changes and/or additions to the ***HANDBOOK.***

Please add my name to your mailing list to be notified of such changes/-additions.

Name ____________________

Firm/Organization ____________________ Phone No. ________

Street (Box No.) ____________________ City ________ State ____ Zip ______

(This sheet may be folded and used as a mailer.)